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TECHNICAL REPORT ECOM-90705-F

RESEARCH AND DEVELOPMENT INTRINSIC RELIABILITY SUBMINIATURE CERAMIC CAPACITORS

FINAL REPORT

BY

T. I. PROKOPOWICZ and A. R. VASKAS

OCTOBER 1969

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CONTRACT NO. DA-36-039-SC-90705

SPRAGUE ELECTRIC COMPANY

NORTH ADAMS, MASSACHUSETTS

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TECHNICAL REPORT ECOM-90705-F OCTOBER 1969

RESEARCH AND DEVELOPMENT

INTRINSIC RELIABILITY

SUBMINIATURE CERAMIC CAPACITORS

FINAL REPORT

1 June 1962 - 31 December 1968

Contract No. DA-36-039-SC-90705
D. A. Project No. 1P6 22001 A 057

Prepared By:

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SPRAGUE ELECTRIC COMPANY

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ABSTRACT

This report presents an approach toward attaining high life test reliability in subminiature ceramic barium titanate capacitors for transistor circuitry and demonstrates a procedure for selecting capacitors having guaranteed or assured lifetime (ALT) at various voltage and temperature stresses. The report presents the research supporting the plan of voltage selection testing which identifies those capacitors that have an assured useful lifetime (ALT). Other selection plans were surveyed but were rejected. The physics of material failure and reliability is discussed. Two lots of 1200 capacitors (0.01 μF and 0.033 μF) were voltage tested to identify capacitors which were predicted to fail life testing either prior to ALT or after ALT. Life testing was as long as 25,000 hours at several voltage and temperature conditions. The failure rate, after normalizing data, at 125°C, 25 VDC to ALT (30,300 hours) for the select 0.01 μF capacitors was 0.02% per 1000 hours. The failure rate after normalizing data at 125°C, 25 VDC to ALT (4775 hours) for the select 0.033 μF capacitors was 0.086% per 1000 hours. The failure rates to ALT for capacitors predicted to fail prior to ALT exceeded the failure rates of the select capacitors by factors approaching 100.

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SECTION 1

PURPOSE

The purpose of this contract was to carry out research work involving investigations leading to approaches for attainment of high reliability in subminiature ceramic capacitors and the determination of failure rate as a function of voltage and temperature.

In particular, this involved the following:

(1) Construction of a model or theory to predict failure mechanisms and failure rates as a function of voltage and temperature.

(2) Development and evaluation of a short-term test to eliminate early failures effectively without shortening the time to the wearout mode of failure.

(3) A determination of the failure rate as a function of voltage and temperature through large-scale life testing. From the data thus obtained, derating curves were to be derived and overall failure rates for operating conditions estimated. The theory developed was to be critically examined and refinements made.

(4) Compilation of quarterly progress reports in accordance with Signal Corps Technical Requirements No. SCL-2101N, dated 14 July 1961.

(5) Compilation of a final report in accordance with Signal Corps Technical Requirements No. SCL-2101N, dated 14 July 1961.

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SECTION 2

PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

2.1 Publications

A paper entitled "Concerning the Physics of Failure of Barium Titanate Capacitors" by D. A. Payne was published in the Sixth Annual Reliability Physics Symposium Proceedings, IEEE, New York, (1968).

A paper entitled "Concerning the Physics of Failure of Barium Titanate Capacitors" by D. A. Payne was presented by Mr. F. W. Perry to the Sixth Annual Reliability Physics Symposium held at Los Angeles, California in November 1967.

2.2 Reports

During the contract period, seventeen quarterly reports were distributed after approval from the U. S. Army Electronics Command. In addition, there was one interim report dated August 1968 submitted. Personnel of the Sprague Electric Company directly involved in generating these reports were: Mr. T. Prokopowicz, Mr. D. A. Payne, Mr. A. Vaskas, Mr. W. A. Tatem, Mr. F. B. Schoenfeld, Mr. J. H. Folster, Mr. P. M. Kennedy and Mr. H. F. Phillips, Jr.

2.3 Conferences

Conferences between personnel of the Sprague Electric Company and representatives of U. S. Army Electronics Command were held at various times throughout the contract period for the purpose of evaluating contract status, reviewing any pertinent problems such as technique or schedule changes, and finding solutions to the problems. Chief Representatives of the U. S. Army Electronics Command were Miss J. Allen, Mr. Herschel Stout, Mr. W. Fontana and Mr. R. Brandmayr. Personnel of the Sprague Electric Company included Mr. J. Fabricius, Mr. T. Prokopowicz, Mr. D. M. Gardner, Mr. J. Michels, Mr. F. Schoenfeld and Mr. A. Vaskas.

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SECTION 3

FACTUAL DATA

3.1 Construction of C67 Case Size I MONOLYTHIC® Capacitors

The 0.01 microfarad (μF) and 0.033 μF C67 Case Size I MONOLYTHIC Capacitors are constructed with stacked ceramic dielectric electrode layers 0.0025 and 0.001 inches thick, respectively. The layers, which are bonded to one another by high-temperature sintering with alternate layers electrically connected in parallel, are composed of barium titanate which has a dielectric constant of approximately 2000 and a stability of +10%, -15% between -55°C and +125°C. The capacitors are enclosed in tubular cases of molded plastic 0.25 inch long with a 0.095 inch diameter.

3.2 Life Test Behavior and Electrical Properties

3.2.1 Typical Life Test Behavior

Typical curves of Resistance vs Time, without interruption of voltage applied to the capacitors, are presented in Figures 1, 2 and 3. During the course of work the C67 formulation (proprietary to the Sprague Electric Company) was modified in the Sprague Electric Company body shop to improve life test behavior. The improvement, reflected in maintenance of high resistance for a longer duration, is evident when the curves of Figure 3 are compared with that of Figure 1.

In the course of a life test, the DC resistance of a capacitor begins at a high level and for a while is maintained or increased and then begins to decrease over several orders of magnitude usually leading to thermal breakdown of the ceramic dielectric. The decrease of resistance with time is termed degradation. The time at which degradation commences is termed onset-of-degradation. For capacitors, such as those whose curves are shown in Figures 1 and 2, and which display a maximum in resistance, the onset-of-degradation may sometimes be termed time-to-peak-resistance, as explained in Section 3.2.4.

The time-to-peak-resistance, t_p, or onset-of-degradation, t_d, depends in an inverse way on applied voltage and temperature. The relationship is presented later.

3.2.2 Consequence of Moisture on Life Test Behavior

It has been postulated that protons in titanate ceramics are a primary cause of capacitor failure. Experiments performed by Linden Laboratories, Inc., have shown that refiring in dry air produces titanate ceramics having longer lifetimes than those which are refired in normal or humid air. (These findings were published in Report No. 20, Contract DA-36-039-AMC-00107(E), dated February 15, 1964.) The dry air refiring withdraws protons introduced into the ceramic during the first firing while humid air refiring causes more protons to enter the ceramic.

In an independent check of these findings, C67 MONOLYTHIC capacitors were refired at 2000°F for 1 hr in flowing air, both dry and humid. These capacitors measured 0.42 x 0.40 x 0.035 in. and contained dielectric layers 0.0025 in. thick. The dry air was produced by passage through a tall column containing granules of anhydrous calcium sulfate (DRIERITE®). Humid air was produced by bubbling through water at either 30°C or 60°C. The silver pickup electrodes used with these capacitors were fired at 1400°F in either dry or humid air, as appropriate to the experiment.

The capacitors for these experiments were made from two different shipments of basic ceramic ingredients. Figure 4 shows resistance-time curves for units made from one of the shipments and presents the best and worst cases of the units refired in dry and in humid air. A curious feature of these curves is the resistance plateau between 300 and 500 hrs, which cannot be attributed to any of the more obvious possible causes. In Figure 5, the average data points for capacitors made from the other shipment of ingredients and refired in dry and in humid air are so nearly identical that only one curve is drawn to represent both conditions.

The dry and humid air refiring experiments were enlarged to include a second titanate ceramic having a dielectric constant of 40 and a TCC of N030 ppm/°C. Figure 6 shows resistance-time curves for discs of this ceramic. In this instance, the discs refired in dry air display more stable curves and higher initial resistance than the discs refired in humid air. Figure 7 shows resistance-time curves for MONOLYTHIC capacitors of this same ceramic. As in the case of the

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disc capacitors, the MONOLYTHIC units refired in dry air show higher initial resistance, as well as high resistance for a longer period of time, than the units refired in humid air. Capacitor No. 756 is typical of the capacitors refired in dry air.

It is tentatively concluded from these experiments that while moisture may detrimentally affect the lifetime of some titanate ceramics, the C67 material in the MONOLYTHIC capacitors appears immune to moisture pickup during a post-firing heat treatment. A firm conclusion regarding the effect of moisture on the C67 material would require a variety of heat treatments in air of different dew points and life testing of capacitors to wearout, probably at temperatures exceeding 150°C.

3.2.3 Electrical Charging and Discharging

The decay of current with time in the external circuit on charging or discharging an ideal capacitor having a series resistance is well known to students of physics and electrical engineering. The decay of current with time in many practical dielectrics appears to be described by a distribution of many time constants and is conveniently expressed over a considerable span of time by $I_{c,d} \propto t^{-n}$, where n has a value near unity.

In practical dielectrics it is suggested that during charging, charges are not only deposited on the plates of the capacitor but charges are also trapped within the dielectric. On discharge, the charges on the plates are quickly removed but the charges trapped within the dielectric are slowly released and the magnitude of the current is measurable for hours.

The circuit used for measuring charge and discharge current is presented in Figure 8. The value of the resistor (incorporated within the electrometer) in series with the test capacitor could be varied between 1 Megohm and 10,000 Megohms.

3.2.3.1 Fresh Capacitors

Charge and discharge curves for C67 MONOLYTHIC capacitors at 25°C and 150°C are shown in Figures 9 and 10. The signs of the currents are omitted for easier comparison of charge and discharge curves (the two currents are opposite in direction). It is interesting to note that the absolute values of charge and discharge currents are similar and can be fitted to the expression $i = i_0 t^{-n}$, over a considerable span of time.

Figure 11 presents a discharge current curve for a C67 Case Size I MONOLYTHIC capacitor near room temperature. This curve was obtained in the following manner: After 15 minutes of discharge, the discharge circuit was opened for 1 hr, then closed again. At this point the discharge current was greater than when the discharge circuit was first opened. Further, after an additional 13 minutes of discharge, the discharge current reached a magnitude and time rate of change that would have been expected had the circuit not been opened. This behavior suggests that charge carrier traps of various depths exist in the material. It is theorized that during the open circuit condition some of the charges move from deep traps to ones which are more shallow.

Figure 12 presents charge current as a function of time at 150°C for C67 Case Size I MONOLYTHIC capacitors. A fresh capacitor was used for each voltage stress to avoid current complications which might result from stressing one capacitor repeatedly. After 15 minutes of charging the currents showed very little indication of stabilizing except at the highest voltage stress.

Over the range of applied voltage the charging current at any time is proportional to the charging potential. At the higher values of applied voltage it is observed that charging current approaches a steady minimum value (See Figure 12).

Following charging, the capacitors used for the test shown in Figure 12 were discharged. The discharge current as a function of time for these capacitors is shown in Figure 13. The value of the discharge current after a particular discharge time is proportional to the charging voltage.

Figure 14 shows charge and discharge current curves for a capacitor charged at 225 VDC, 100°C and discharged, then charged at -225 VDC, 100°C and discharged. The magnitude of the charging and discharging currents in each instance is the same.

Figure 15 presents discharge curves for the improved C67 ceramic and the obsoleted ceramic. The values of the discharge currents are similar.

Figures 16 and 17 present charging curves at 85°C and 150°C, with applied voltage as a parameter, for the improved C67 ceramic. Figures 18 and 19 present charging curves at 93 VDC and 200 VDC applied, with temperature as a parameter. The distinguishing feature of the improved C67 ceramic, compared with the former ceramic, is that the currents attain a steady-state value quickly (i. e. currents do not change with time).

3.2.3.2 Degraded Capacitors

Degradation was defined in Section 3.2.1. The charging and discharging behavior of degraded capacitors compared with fresh or new capacitors is of interest.

Figure 20 presents charge and discharge current curves for a capacitor which had been life-tested previously at 150°C and 75 VDC/mil for 1600 hours. During the life test the resistance of the unit decreased approximately four orders of magnitude. The degraded capacitor was charged for 15 minutes at 100°C and 225 VDC in the same direction as during life testing, then discharged. The corresponding charge and discharge curves for this operation are labeled (+) on the figure. Following discharge the capacitor was charged in the direction opposite the charging direction during life testing, then discharged. The corresponding charge and discharge curves for this operation are labeled (-) in the figure. It will be observed that the discharge curves are approximately one order of magnitude apart. For comparison, a fresh capacitor was charged in one direction and discharged, then charged in the opposite direction and discharged. The resulting discharge curves are within 20% of one another, as can be seen in Figure 14. The data suggest that ionic migration resulting from life testing leads to charge carrier traps of different average depth in the proximity of each electrode. This hypothesis assumes that release of trapped charges is effected by thermal energy.

Figure 21 presents charging currents at 85°C for new and aged capacitors. The capacitors were previously degraded at 150°C to the values indicated in the figure. The time to reach steady-state current is much less for the degraded parts and decreases with increased level of degradation.

3.2.3.3 Single Crystal Barium Titanate

The magnitude of the discharge or depolarization currents observed for the C67 MONOLYTHIC capacitor raises the question of their origin. It is not known whether these currents are primarily related to the polycrystalline form of the material, with its attendant defects such as grain boundaries and closed pores, or whether they are related primarily to the bulk or surface characteristics of the crystal structure itself. It appears that the polycrystalline form is of secondary importance in determining the occurrence of the discharge currents. Figures 22 and 23 show discharging currents of barium titanate single crystals prepared by the Remeika technique. These currents are approximately 100 times greater than the discharge currents of a C67 capacitor under comparable conditions of charging. The

discharge currents are presented in Figure 24. While the chemical composition of the single crystals differs from that of the ceramic they are both essentially barium titanate, and it can be concluded that the discharge currents of the C67 material are not a consequence of its polycrystalline form.

3.2.3.4 Repeated Charging

Figure 25 presents charging current data for a capacitor charged until minimum current was attained five times at 150°C. Between charging periods the capacitor was maintained at either 150°C or 25°C. The time-to-minimum-current (onset-of-degradation) was to some extent affected by previous chargings, but any damage suffered by the capacitor was evidently repairable to a considerable degree by resting, particularly at a temperature of 150°C for 69 hours.

Repeated charging was extended to include a degraded capacitor. A new capacitor was subjected to 95 VDC (38 V/mil) at 150°C until its resistance had degraded from a maximum resistance (point of minimum current) of 1,200,000 MΩ, to approximately 10,000 MΩ, at which point the voltage was removed, and the capacitor was allowed to rest for various periods of time with its terminals connected through a 1 MΩ resistor or unconnected. The behavior of the current following rest periods is presented in Figures 26 and 27. Within a few minutes after each rest period, the current achieved a stable value which was commensurate with its value when removed from life test.

A capacitor charged for a period of time short of onset-of-degradation may be repeatedly charged, after resting, without appreciably changing the time to onset-of-degradation. A period of rest at 150°C does not "rejuvenate" a severely degraded capacitor.

3.2.4 Steady-State Electrical Conductivity

3.2.4.1 Fresh Capacitors

The electrical conductivity of the C67 ceramic depends on temperature, applied voltage and time. The temperature-time dependence is graphically illustrated in Figure 18 and the applied voltage-time dependence in Figures 16 and 17. There is a time at each applied voltage and temperature when the conductivity is constant with time and is generally referred to as steady-state conductivity. The duration when the conductivity does not change with time may be brief, such as a few minutes, or it may be almost indefinite, depending on applied voltage and temperature. The time required to reach steady-state

conductivity is referred to as time-to-minimum-conductivity or time-to-peak-resistance. The time of passage from steady-state conductivity to increasing current with time is called time-to-onset-of-degradation. When steady-state conductivity persists for only a brief time then the terms time-to-peak-resistance and time-to-onset-of-degradation may be used interchangeably.

The electrical conductivity of the C67 ceramic is conveniently described by the steady-state conductivity, which removes the confusing element of time.

The steady-state current of fresh C67 capacitors at 85°C and 150°C as a function of applied field is presented in Figures 28 and 29. The conductivity is ohmic to nearly 100 V/mil, above which it is markedly non-ohmic. The conductivity of the C67 ceramic may therefore depend on applied field, independent of time.

The activation energy for conduction as a function of temperature, calculated from steady-state conductivity, is 0.79 electron volts. The data from which this value is computed are presented in Figure 30.

Steady-state conductivity for the improved C67 ceramic at 85°C and 150°C as a function of applied voltage is presented in Figures 31 and 32. The electrical conductivity is somewhat non-ohmic.

The activation energy for electrical conduction as a function of temperature for the improved C67 ceramic, calculated from steady-state conductivity data, presented in Figure 33, is 1.00 electron volts. The increased activation energy for the improved C67 ceramic over the obsoleted ceramic may be a key factor for improved lifetimes (compare Figures 1 and 3).

3.2.4.2 Degraded Capacitors

Figure 21 indicates that the term steady-state conductivity may be applied to degraded capacitors. The time needed to attain electrical conductivity which does not change appreciably with time decreases as the degree of degradation is increased.

Figure 34 shows steady-state current as a function of applied field at 85°C for a capacitor which was mildly degraded at 150°C. The current values are higher when the same voltage polarity is used for conductivity measurement as for producing degradation than when the voltage polarity is reversed. The current-voltage (I-V) relation is slightly non-ohmic but to the same degree in each case. Figure 35 presents I-V relations at 85°C for degraded capacitors compared to a

fresh non-degraded capacitor. The degraded capacitors are non-ohmic while the fresh capacitor shows a near-ohmic relation over much of the voltage range.

Figure 36 shows the relationship between resistance and temperature for several capacitors degraded about four orders of magnitude by life testing at 150°C. It is notable that the activation energy for conduction of degraded parts is 0.79 electron volts, equal to that of fresh capacitors (Figure 30).

Figure 37 presents the I-V relation at 150°C for a slightly degraded capacitor made from improved C67 ceramic. The relationship is somewhat non-ohmic for the degraded capacitor but non-degraded capacitors display somewhat non-ohmic relation (Figure 32) too.

3.2.5 Voltage Reversal During Life Testing

It may be postulated that degradation is the consequence of ionic transport due to the impressed electric field during life testing. The most likely ionic species to be transported are oxygen ions and charged oxygen vacancies. If oxygen ions are lost from the ceramic without an equal loss of oxygen vacancies, irreversible damage may be assumed to have occurred. If both oxygen ions and vacancies are transported only short distances in the ceramic by an impressed electric field it may be assumed that an electric field can return the ionic species to nearly their original positions.

On these premises, it may be postulated that life testing to the onset-of-degradation or slightly beyond produces reversible damage while life testing so as to effect severe degradation produces irreversible damage. Reversible damage may be undone by reversing the sense of the applied voltage.

Figures 38 and 39 present data for capacitors life tested with voltage of one sense to the extent of producing mild degradation. Reversing the applied voltage appears to have undone the damage of the initial voltage application, judging from a comparison of the times to the onset-of-degradation for each sense of voltage application.

A moderately degraded part may be somewhat rejuvenated by voltage reversal. Figure 40 presents data for such a capacitor. In the course of 1700 hours a capacitor was degraded from 15,000 MΩ to 70 MΩ. On voltage reversal, the resistance increased to 600 MΩ and 1500 hours of voltage application elapsed before the resistance was again degraded to 70 MΩ.

The experiments on voltage reversal during life test suggest that assured lifetime capacitors may be selected on the basis of voltage application for a period of time and reversal of voltage for a period of time to undo or repair the damage produced by initial voltage application. To minimize the time required for selecting assured lifetime capacitors, the relationship of temperature and voltage conditions during selection to the conditions of operation must be known.

3.2.6 Dependence of Onset-of-Degradation On Temperature and Voltage

The relationship between time-to-peak-resistance, (t_p) and temperature at a fixed voltage of 220 V is shown in Figure 41. This relationship has the form of:

$$t_p = t_o \exp\left(\frac{\Delta w}{kT}\right), \text{ where } \Delta w = 0.90 \text{ eV}$$

The relationship between time-to-peak-resistance, t_p, and voltage at 150°C is shown in Figure 42. The time-to-peak-resistance is strongly dependent upon voltage, being inversely proportional to $V^{+2.7}$.

The voltage and temperature conditions chosen were such that the duration of steady-state current was brief, so little error results when the terms time-to-peak-resistance and time-to-onset-of-degradation are used interchangeably as explained in Section 3.2.4.

The time to the onset-of-degradation at temperatures like 125°C and 85°C with voltages lower than 220 V was not determined because the times would obviously be very long.

Times to the onset-of-degradation as a function of voltage and temperature for the improved C67 ceramic were not determined because the times would be extremely long as indicated by an examination of Figure 43. It is presumed the voltage-temperature dependence of the onset-of-degradation for the improved C67 ceramic is the same as determined on the earlier C67 material.

3.2.7 Assured Lifetimes

The assured lifetime (ALT) is the guaranteed period over which the capacitor can survive a given voltage/temperature condition. ALT can be attained by subjecting the capacitor for a period of time at a temperature and voltage more severe than expected operating conditions and then reversing voltage polarity for an equal period of time.

It is necessary that the capacitor be no more than mildly degraded, and preferably the onset-of-degradation not to have been exceeded, for a capacitor to be acceptable. A capacitor displaying moderate or severe degradation is to be rejected. The degree of acceptable degradation is probably about one order of magnitude and preferably less.

The temperature, or voltage or time for ALT may be calculated using the following generalized equation:

$$t_1 = t_2 \left[\frac{E_2}{E_1}\right]^{2.7} \exp\left[\left(\frac{0.90}{k}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \quad (1)$$

where t_1, t_2 = performance times under conditions 1 and 2, respectively

E_1 E_2 = volts/mil or volts for conditions 1 and 2, respectively

k = Boltzmann's constant (0.0000862 ev/°K)

T_1 T_2 = Kelvin temperature conditions 1 and 2, respectively

The following example computations illustrate the use of the generalized formula:

ALT			Selection Conditions		
E_2	T_2	t_2	E_1	T_1	t_1
100V	85°C	32,000 hrs.	400V	150°C	9 hrs.
200V	85°C	4,000 hrs.	400V	150°C	7 hrs.
100V	125°C	8,000 hrs.	400V	150°C	40 hrs.
200V	125°C	4,000 hrs.	400V	150°C	126 hrs.
200V	125°C	1,000 hrs.	400V	150°C	32 hrs.

It must be recalled E_1 is reversed for an additional period of time equal to t_1 to attain ALT.

3.2.8 Current-Voltage Plots and Correlation to Life Test Capability

During the course of this program, the life test behavior of several lots of capacitors was observed. It was noted that the time to the onset-of-degradation might vary considerably from one lot to another.

It was also noted that plots of steady-state current versus applied voltage also varied considerably from one lot to another.

Figures 44 and 45 show an I-V plot and life test plot at 150°C, respectively, for lot D269, C67 capacitors. The I-V plot is markedly non-ohmic at the life test voltage and the onset-of-degradation is about 2 hours.

Figures 46 and 47 present an I-V plot and life test plot at 150°C, respectively, for lot D128, C67 capacitors. The onset-of-degradation is about 50 hours and while the I-V plots are markedly non-ohmic the departure from ohmic at life test conditions is not as pronounced as for lot D269.

Figures 48 and 49 are I-V and life test plots for lot X950A, C67 capacitors, respectively. The onset-of-degradation has not been reached even after 700 hours and the I-V plot at life test conditions is only slightly non-ohmic.

Figures 50 and 51 are I-V and life test plots for lot 830, C67 capacitors, respectively. The I-V plot at life test conditions is only slightly non-ohmic and the onset-of-degradation appears to be beyond 2000 hours.

The implication from the preceding data is that capacitors displaying near ohmic I-V plots at life test conditions will have their onset-of-degradation at a later time than capacitors displaying markedly non-ohmic I-V plots. In addition, it would appear that near-ohmic I-V plots at temperatures and voltage exceeding operating conditions of the capacitors would be desirable.

Because of the interesting correlation between the character of the I-V plots and life test behavior for C67 capacitors, capacitors made from other titanate materials were examined.

Figures 52 through 55 present I-V relationships and life testing behavior for C25 and C75 composition MONOLYTHIC capacitors. These compositions have room temperature dielectric constants of 36 and 115, respectively, and capacitance temperature coefficients of -30 and -750 ppm change/°C, respectively. Both types exhibit near-ohmic current-voltage relationships and stable behavior on life test.

Figures 56 through 59 present steady-state current versus applied voltage plots and life testing behavior for C73 composition MONOLYTHIC capacitors. The C73 ceramic composition has a room temperature relative dielectric constant of 1500 and a temperature coefficient of capacitance tolerance of ±10% with respect to 25°C in the

range -55°C to 125°C. Both Lot No. X930B and Lot No. X958B MONOLYTHIC capacitors exhibit near-ohmic I-V relationships, and both exhibit identically stable resistance-time relationships for the first 80 hours of life testing. However by 180 hours, Lot No. X958B capacitors have dropped in resistance by three orders of magnitude while Lot No. X930B capacitors show negligible resistance change even after 700 hours.

The experimental evidence allows several tentative conclusions:

1. Ohmic or near-ohmic steady-state current versus applied voltage plots usually indicate long-life titanate dielectrics.

2. The degree of departure from ohmic in an I-V plot cannot be exactly correlated to the time-to-onset-of-degradation since it is known that this depends on applied voltage stress at a given temperature.

3. The influence of construction defects leading to early capacitor failure possibly are not reflected in an I-V plot.

3.3 Concerning the Physics of Failure of Barium Titanate Capacitors

During this program to develop high-reliability, subminiature, ceramic capacitors, it was noted that during sustained direct voltage at elevated temperatures dielectric breakdown occurred only in units whose voltage-current characteristics before life test had been significantly non-ohmic (Section 3.2.8).

An argument is presented that migrating oxygen vacancies would gradually build up a positive space-charge layer at the cathode interface, bringing about a reduction in the apparent work function required for electronic injection. By analogy to the Richardson-Schottky effect, the thickness of the defect layer was calculated to be of the order of 100-1000 Å sustaining a breakdown field greater than 10^8 V/cm.

3.3.1 Conductivity Characteristics

Typical charging-current characteristics are illustrated in Figure 60. At low voltage stresses, the time constant was extremely long. Over a period of many months, it was continually noted that units

whose previous steady-state or equilibrium current-applied voltage characteristics were significantly non-ohmic, i.e., $I_E \propto V^n$, and $n \geq 1.8$ (Figure 61), eventually failed on life test (Figure 62). Near-ohmic units did not fail (Figures 61 and 62). From Arrhenius studies of the unreliable, non-ohmic units, the activation energy for conductivity was found to be dependent upon the applied field strength (as shown in Figure 63), i.e.,

$$I_E = I_o \exp\left(\frac{-W_{(F)}}{kT}\right) \qquad (2)$$

where:

$$W_{(F)} = W_o - B\sqrt{F} \qquad \text{(Figure 64)} \qquad (3)$$

F is the applied field strength and B is a positive constant. Therefore,

$$I_E = I_o \exp\left(\frac{-W_o}{kT}\right) \exp\left(\frac{B\sqrt{F}}{kT}\right) \qquad (4)$$

where the equilibrium current is dependent upon two activation energies. The unusual dependency of log I_E on $\sqrt{F}$ is more clearly illustrated in Figure 65.

The ceramic materials which exhibited this characteristic developed definite Galvani EMF's when placed in an oxygen concentration cell without bias[1]. See Table I for the reaction equations and values observed.

The potential of an electrochemical cell is solely due to ionic effects. The polarity of the EMF reversed when the concentration gradient was reversed. It therefore appears that the $\sqrt{F}$ dependency may be related to oxygen ion (and consequently, oxygen vacancy) transport.

3.3.2 Ionic Space-Charge and "Schottky" Type Emission

Under prolonged application of a DC bias on actual life test, there would be a drift of oxygen ions towards the anode and of vacant oxygen sites towards the cathode.

The vacancies have an effective 2+ charge and eventually a positive space-charge region would build up at the cathode interface. The counterflow of oxygen ions towards the anode would form a negative space-charge layer on the ceramic surface at the electrode. Noble

metals are known to form a conducting oxide monolayer[2] and a probable reaction at the palladium anode would be:

$$2O^{2-} \longrightarrow O_2 + 4\bar{e} + 2\square^{2+} \tag{5}$$

where $\square^{2+}$ represents a vacant oxygen site.

The electronics released by this reaction are thought of as going principally into the band structure of the metal, but it is also possible that a few may be taken up by the Ti^{4+} ions according to the reaction:

$$Ti^{4+} + \bar{e} \longrightarrow \underset{\text{(blue)}}{Ti^{3+}} \tag{6}$$

The elevation of a 2p electron from an O^{2-} ion into the 3rd band of the Ti^{4+} ion creates a positive hole which may now move toward the cathode together with the recently replenished vacancies provided by Reaction (5). The atomic or molecular oxygen produced by Reaction (5) could continue to exist in the system nonstoichiometrically.

The resulting equilibrium current was previously shown to be activated by the temperature and the applied field strength. Such a dependency is similar to the Richardson-Schottky effect. A modification of Richardson's formula takes into account electrons being injected into a dielectric instead of a vacuum.

Recent investigations have noticed similar characteristics for thin mica[3], metal-oxide films[4], oil-impregnated paper[5] and organic insulating films[5].

$$I_E = SAT^2 \exp\left[\frac{(-\phi)}{(kT)}\right] \exp\left[\frac{(C\sqrt{F})}{(kT)}\right] \tag{7}$$

where S = electrode area
q = electronic charge
k = Boltzman constant
d = dielectric thickness
A = experimental constant depends upon type of material

$$C = q^{3/2} (a/4\pi\epsilon d)^{1/2} \tag{8}$$

ϵ = dielectric constant

By analogy to Schottky's original equation, a in this expression takes into account the increase in field-strength at the cathode due to the space-charge effect[5].

3.3.3 Mechanism of Dielectric Breakdown

The constant drift of vacant oxygen sites toward the cathode will bring about a nonlinear field distribution(6). As testing time progresses, these defects form a virtual anode within some critical distance X_O from the cathode and an appreciable amount of the applied voltage, V_A, falls across this gap.

The increase in the effective field at the cathode interface ($\alpha \frac{V_A}{d}$) due to the positive space-charge layer will eventually cause catastrophic failure.

At low applied voltages, electrons drawn out of the cathode are trapped in the defect layer and the current is limited. Blue color centers have been observed at the cathode. A critical voltage, V_B, exists, however, where the effective field strength, F, between the cathode and the virtual anode becomes sufficient to flood the defect layer with electrons (the trap-filled limit) and the electrons may now enter the conduction band by either a Poole-Frenkel mechanism or by a collision-ionization process. Here again the current may initially pass through a minimum because of trapping (Figure 60), but soon begins to climb rapidly and dielectric breakdown eventually occurs.

3.3.4 Calculation of Dielectric Strength

The dielectric constant for the barium titanate-based ceramic was 690 at 150°C and 1.5×10^4 V/cm. Values of d/α calculated from the slope data of Figure 64 and Equation (8), were found to be 100-200 Å. The field strength across this depletion layer, below V_B, was less than 10^6 V/cm which is typical for Schottky emission. Above V_B, the field intensity became greater than 10^8 V/cm, which is sufficient for avalanche flow of electrons by an ionization process.

3.4 Screening for the Selection of Long Life Capacitors

One of the objectives of this program was the development of methods for detecting capacitors which would have short lifetimes if placed on life test, or the development of methods for detecting capacitors which would have long lifetimes if placed on life test. In either case, capacitors not excluded from service would perform very reliably when placed in service. The duration of reliable service, it was understood, would be about three years at temperatures and voltages suitable for transistor circuitry.

The most severe temperature and voltage for transistor circuitry are probably 125°C and 30 VDC. Indeed, transistor reliability usually requires less severe operating conditions, particularly in complex

circuitry. It is known that the average lifetime of subminiature ceramic capacitors is very long in transistor circuitry, therefore, reliability testing of ceramic capacitors, for convenience sake, had to be at conditions of voltage or temperature exceeding service conditions. Performance deceleration factors due to increased temperature or voltage were developed in Section 3.2.6.

One systematic way of seeking out methods or techniques for the identification of capacitors which might be expected to have either a short or a long lifetime on life test is to place thousands of capacitors on life test at conditions hardly more severe than service conditions for thousands of hours and as capacitors fail, identify failure modes and establish what mechanisms were involved. Once the mechanisms are known, detection techniques are developed for the presence and intensity role of that mechanism expected from the capacitor in service. The detection techniques are used to select long-life capacitors or to reject short-life capacitors, or both.

The time allotted to this program was originally 18 months. Therefore most life testing had to be conducted at severe operating conditions if failures were going to be produced in a reasonable time. It was discovered that failure analysis was extremely difficult. Although the mechanism appeared always to be the same, as proposed in Section 3.3, the detection techniques for the mechanism and the intensity of its presence took time to develop. The detection technique described in Section 3.2.7 is probably the best available but requires much refinement.

Because the time for this program originally appeared very limited, techniques for the detection of potential early failure capacitors were evaluated from the commencement of this program, although basic knowledge such as presented in Section 3.2 and 3.3 was largely lacking. While some results are negative, the work is reported largely for the sake of record and completeness.

3.4.1 Corona Starting Voltage

The attempt was made to correlate 60 Hz corona starting voltage and time-to-failure of the capacitors on DC life test. The location of the corona may be in voids or cracks within the dielectric material or between the electrodes and dielectric surface in certain instances. It is conceivable that such defects might influence capacitor lifetime.

In determining corona starting voltage each capacitor was flashed with 30 VAC when the testing apparatus switch was turned on. The voltage was then slowly increased until corona spikes were seen on

the oscilloscope screen. A 0.01 inch deflection on the oscilloscope screen was equivalent to 0.4 mV. The equipment produced no corona below 2000 VAC.

The relationship between corona starting voltage for 27 capacitors and time-to-failure is presented in Figure 66. There is apparently no correlation. The parts subjected to corona testing failed within the same time span as the parts not subjected to corona testing. The life test conditions are severe (185 VDC, 150°C) and it can be said that the test did not include parts which failed after a short time at severe conditions (earliest failure at about 60 hours) so the value of corona starting voltage for detecting potential early failures under service conditions as found in transistor circuitry remains an open question. Based on 60 hours life at 150°C, 185 volts, performance times at less severe conditions can be calculated.

EQUIVALENT PERFORMANCES TIMES*

Voltage DC	Temperature °C	Hours Duration
185	150	60
50	125	9,300
30	125	37,000
50	85	172,000

*Assumes the validity of temperature and voltage factors presented in Section 3.2.6 for cases well beyond onset-of-degradation.

3.4.2 Voltage Conditioning

An early proposal in this program was the selection of long life on the basis of electrical measurements, following conditioning of the capacitors with AC or DC voltage, for a period of time, at an elevated temperature.

Ninety capacitors of 4000 μμF capacity were obtained for the voltage conditioning experiments. The capacitors were divided into five groups, each group undergoing a series of tests and measurements as described in Figure 67. As can be seen in this figure, this voltage conditioning experiment included measurements of the electrical resistance of the units at various stages of the test sequence before the life test.

Measurements were made on all five test groups for resistance at 25°C and 150°C with voltages of +100 VDC applied. In

addition, resistance was periodically measured on the units undergoing test at +225 VDC, 150°C, for 50 hr (Test Group IV).

While the voltage conditions for the various tests are given in terms of positive and negative, it is not intended to imply that the test units were polar when manufactured. Positive and negative terminals were arbitrarily assigned to the units because the units were to undergo several DC measurements and tests.

Periodic resistance measurements were made during the accelerated life test to which all units were subjected. These measurements were made without interruption of the test. This was accomplished by measuring the voltage drop across each unit and also across a 1 MΩ resistor permanently in series with it. These voltage drops were then used to calculate the resistance of the unit.

3.4.2.1 Test Results

There were no electrical resistance failures before life testing. At Point C in Figure 67 the resistance remained above 100 MΩ. The choice of failure definition was not entirely arbitrary. As the data reveal, a resistance of 100 MΩ or less at 150°C is a decrease of approximately three orders of magnitude from a new, unstressed unit. A resistance change of this degree definitely indicates that the capacitor is wearing out. Figures 68 and 69 show a comparison of the life test performances of the five groups of units. In examining these data, it must be borne in mind that Life Tests H and I shown in Figure 67 are at severe conditions, i.e., 150°C, approximately 75 V/0.001 in. These conditions were chosen in order to obtain useful life performance data in a reasonable period of time. A comparison of the life test performances of Groups I, II and III with Group V, the control group, indicates that the AC conditioning voltages applied to these groups (Tests D, E, F, in Figure 67) before life test had little or no effect on the average time to failure. The application of +225 VDC for 50 hr (Test G in Figure 67) produced a polarity on the Group IV units which resulted in a wide variability of life times on the life test. The life performance of the Group IV units subjected to the +225 VDC conditioning and tested at +190 VDC were inferior to those of the control group (Group V). The life performances of the Group IV units tested at -190 VDC were superior to those of the control units. This difference in performances is due to the predominantly ionic nature of titanate dielectric wearout. This ionic nature may explain why AC burn-in had negligible effect on the life performance of the units, particularly since the temperature rise of a unit subjected to 60 Hz AC voltage is calculated to be approximately 2°C above ambient.

One conclusion possible from Figure 69 is DC voltage conditioning will add to the life time of capacitors, if the life test is of the opposite polarity to voltage conditioning, and detract from the lifetime if the life test is of the same polarity.

The data were inspected to see if a correlation existed between measurements made at Points marked C in Figure 67, i.e., resistance at 150°C before life testing and time to failure on life testing (Points H and I). The resistance measurement at 150°C, prior to life testing, was recorded after 30 minutes of electrification. The data indicated that no usable relationship exists between resistance before life test and time-to-failure. The application of AC or DC voltage for a time does not condition a part so that an early failure can be detected. Time-to-failure for the 90 capacitors ranged between 200 hours and 1000 hours. It is conceivable that parts failing after 10 to 20 hours of life testing might have exhibited resistance values markedly different from those failing between 200 and 1000 hours.

3.4.3 Electrical Charging or Discharging Currents

The features of electrical charging and discharging currents were described in Section 3.2.3. Inasmuch as charging and discharging currents cannot be described simply by a capacitor with a series resistance, it was suggested that the values of discharge currents might serve as indicators of performance on life test (Linden Laboratories, Inc., "Crystal Chemistry of Ceramic Dielectrics," Report No. 15, July 15, 1962, Contract No. DA-36-039-SC-78912).

An investigation was begun to learn if a correlation existed between the prior measured value of charging or discharging current and time to failure on life test conducted at severe temperature and voltage conditions. Life testing of the capacitors was at 150°C and 190 VDC (75 V/mil), and a capacitor was defined to be a failure when its resistance dropped below 10 MΩ, indicating degradation of nearly four orders of magnitude in resistance from that of a fresh unit.

No correlation of charging current at two minutes or 15 minutes after start of charging to time-to-failure exists (Figures 70 and 71). Nor was there correlation between the value of discharge current after two minutes or 15 minutes of discharge and time-to-failure (Figures 72 and 73).

In another experiment, a group of capacitors was conditioned or "burned-in" with 190 VDC at 150°C for 24 hours before charge and discharge currents were measured. No clear-cut correlation between charging current or discharging current and time-to-failure exists for parts previously conditioned with DC voltage (Figures 74, 75 and 76).

It appears that the value of charging or discharging current after a period of time cannot be used to select long-life capacitors. The data are insufficient to state whether or not charging or discharging current values can indicate short-life capacitors. The times to failure at accelerated life testing conditions in the experiments ranged between 100 hours and 1300 hours. One hundred hours of life at 190 VDC and 150°C is the computed equivalent of more than 37,000 hours at 30 VDC and 125°C (Section 3.4.1), the conditions for transistor circuitry operation. The experiments would have been more revealing had three or more orders of magnitude in lifetime at accelerated conditions been spanned, instead of one.

3.4.4 Time to Onset-of-Degradation and to Failure

Earlier in this report (Section 3.2.1) capacitor resistance behavior with time during life testing at accelerated conditions was described. At the start of this program, test capacitors were characterized by an increasing resistance for a period of time until a peak resistance was attained, which for a brief time could be called a steady-state resistance, followed by decreasing resistance value inversely proportional to about the 3rd power of time (Figures 1 and 2). In the instance of these early capacitor models, very little error was involved if time-to-peak-resistance and time-to-onset-of-degradation were considered to be the same numerically. It was determined that time-to-onset-of-degradation was a function of temperature and voltage (Section 3.2.6).

An experiment was conducted to determine if, from measurements of t_p (time to peak resistance) and R_p (peak resistance) at a high temperature, the lifetimes of a capacitor at a lower temperature might be predicted. It is believed that the measurement for t_p and R_p does not appreciably detract from the lifetime of a capacitor (Section 3.2.3.4).

For times beyond peak resistance, the resistance of a capacitor with time may be approximated as follows:

$$\log R = \log R_1 - g \log t; \text{ or} \qquad (9)$$

$$R = R_1 t^{-g} \qquad (10)$$

where:

g is degradation constant $\dfrac{\Delta \log R}{\Delta \log t}$; and

$$R_1 = R_p t_p^{\,g} \qquad (11)$$

Substituting in Equation (10):

$$R = R_p\, t_p{}^g\, t^{-g} \tag{12}$$

If a resistance value defining failure, R_f, is established, an approximate life time formula can be written by transposing the elements in Equation (5) as follows:

$$t_f = \frac{R_p{}^{1/g}\, t_p}{R_f{}^{1/g}} \tag{13}$$

where: t_f is time to failure.

Any prediction of capacitor life based on Equation (13) is expected to be conservative since it does not take into account the fact that the degradation rate (g) at the onset-of-degradation is much less than after degradation is established (Figures 1 and 2).

Twenty-seven capacitors from three manufacturing lots were chosen for the experiment. Measurements of t_p and R_p at 150°C and 185 VDC were performed on each capacitor. The capacitors used in the experiment ranged in capacity from 6,000 pF to 10,000 pF. It was found that the capacitors which have high values of peak resistance, R_p, generally also have high values of t_p (Figure 77).

Life testing on these capacitors consisted of 340 hours at 85°C, 100 VDC, followed by 1500 hrs at 85°C, 200 VDC, and then by 2350 hrs at 105°C, 200 V.

The time-to-peak-resistance, t_p, at temperatures and voltage other than t_p, was measured and may be computed using the relations given in Section 3.2.6 (Figures 41 and 42). Peak resistance at any temperature may be computed, if it is known at a particular temperature (Figure 30).

If values for t_p and R_p are known at 150°C and 185 VDC the values at 85°C, 105°C and various voltages may be computed and placed into Equation (13). A value for degradation constant, g, must be estimated. Although the value 3 seems reasonable for 150°C (Figures 1 and 2), the value of g at lower temperatures may be different. An extreme example would be if g were extremely large. In such a case Equation (13) would indicate $t_f \approx t_p$.

Life test data together with values of R_p and t_p and calculated lifetime, using Equation (13), at 105°C, 200 VDC are presented in Table II. Failure resistance, R_f is 100 MΩ at the test conditions. A value of g equal to 5 was assumed.

An examination of the data (Table II) indicates that the test performance of capacitors at 105°C having t_p at 150°C greater than 240 minutes was far superior to capacitors having t_p of short duration. In this experiment values of t_p spanned two orders of magnitude, which lends support to the usefulness of t_p data.

The other observation is that calculated lifetimes, t_f, were far less, generally, than actually measured. A conservative computation was expected because of the difficulty of assigning a value to g not only in the neighborhood of t_p but after degradation was under way.

3.4.5 Selection of Assured Lifetime (ALT) Capacitors

The concept of Assured Lifetime (ALT) was presented earlier (Section 3.2.7). ALT is the guaranteed period over which the capacitor can survive a given voltage/temperature condition. A part of selection for ALT is subjecting the capacitor for a period of time at a temperature and voltage more severe than expected operating conditions and then reversing voltage polarity for an equal period of time (Section 3.2.5). Providing that time to the onset-of-degradation, t_d, has not been exceeded, or only slightly exceeded, the initial voltage application produces damage that can be reversed by the application of voltage of the opposite sense. Having demonstrated a voltage capability at a severe operating condition and subsequently restored the capacitor to its "virgin" state, ALT may be computed (Section 3.2.7). In principle, if it has been determined that a capacitor has not reached onset-of-degradation at a certain condition of voltage and temperature, then what that time duration is equivalent to at other conditions of voltage and temperature can be computed. The computed time duration is ALT. ALT is a cautious concept in that the failure point, R_f, may be three or four orders of magnitude less than peak resistance, R_p, and the time span between R_p and R_f may be great depending on the time to the onset-of-degradation, t_d, and the degradation constant g (Section 3.4.4).

An experiment involving 122 capacitors was set up to evaluate the idea of ALT. The experiment is outlined in Figure 78. Of these 122 capacitors 53 were subjected to the two-part screening program which is incorporated into the experiment. The screening program comprised the following steps:

Step 1 - The capacitors were subjected to 300 VDC at 150°C for 72 hours. Resistance was read at 1 hour and 72 hours.

Step 2 - The acceptable capacitors from Step 1 were subjected to -300 VDC at 150°C for 72 hours.

Three capacitors in Step 1 displayed untypical behavior (Figure 79). These capacitors were not subjected to Step 2. Distribution of measured properties of capacitors subjected to Step 1 are presented in Figures 80 and 81. These figures indicate what is meant by untypical and typical behavior. Capacitors displaying untypical behavior are suspected of poor life test performance.

The purpose of Step 1 of the screening program is to identify those capacitors which have not reached the onset-of-degradation. Capacitor Nos. 253 and 260 may be said to be considerably beyond onset-of-degradation.

The purpose of Step 2 of the screening program is to rejuvenate normal capacitors; those not having greatly exceeded onset-of-degradation, and to detect those capacitors which might be sensitive to polarity because of some construction or material defect. None of the capacitors subjected to Step 2 indicated untypical behavior (Figures 82 and 83).

In this experiment if the resistance of a capacitor did not change more than ±20% between 1 hour and 72 hours at 150°C, 300 VDC in either Step 1 or Step 2 it is assumed that the onset-of-degradation has not been reached. None of the capacitors subjected to Step 2 was stressed beyond the onset-of-degradation.

The assured lifetime (ALT) for the capacitors in Step 2 is computed.

ALT's Based on 72 Hours, 300 VDC, 150°C

Temperature	Voltage	ALT
125°C	200 VDC	1000 hours
125°C	100 VDC	38 weeks
125°C	50 VDC	4.8 years
85°C	200 VDC	2.2 years
85°C	100 VDC	14 years
85°C	50 VDC	89 years

The 122 capacitors were placed on life test at 125°C, 200 VDC for 2300 hours followed by further life testing for a period of 30,000 hours (3.4 years) at 125°C, 400 VDC.

The 53 capacitors from Step 2 screening life test cells A and B had a computed ALT of 1000 hours at 125°C and 200 VDC. At the end of 1000 hours at 125°C and 200 VDC none of the 53 capacitors had failed (R_f = 100 MΩ), indeed, none of the capacitors had reached the onset-of-degradation, td.

Further examination of the life test data (Table III) for the 53 capacitors revealed onset-of-degradation was not reached even after 2300 hours at 200 VDC and 125°C. Among the 53 capacitors, two capacitors in Cell B indicated beyond onset-of-degradation at 1100 hours of testing at 400 VDC and 125°C. One of the two capacitors indicated failure (R = 25 MΩ, R_f = 100 MΩ) after 6100 hours at 400 VDC and 125°C.

The Life Testing Summary (Table III) indicates the quality of the capacitors in Cells A and B far exceed ALT. No computation of ALT for the capacitors in the other life test cells was possible because none of them was subjected to Step 2 screening (Figure 78). At first glance it might appear than an ALT computation could have been made for the capacitors in Cell D inasmuch as the test voltage in Cell D and the screening voltage in Step 1 were in opposite directions, based on the principle that a reversed voltage should restore the capacitors to their "virgin" state (Sections 3.2.5 and 3.4.2).

However, a purpose of Step 2 conditioning and screening, besides rejuvenation of the capacitors, is to detect those capacitors which might be sensitive to polarity because of a defect in construction or material. Although the first capacitor in Cell D which failed on life test passed Step 1 (Figure 79, Capacitor No. 246) it may be stated that the capacitor would not have passed Step 2 (Table III).

A conclusion from this testing is that any procedure employing DC voltage conditioning of titanate monolithic capacitors to ensure performance reliability should specify voltage reversal (Table III).

Capacitor Nos. 253 and 260 (Figure 79) were tested in Cell C (Figure 78, Table III). Neither of these capacitors failed life test although during the term of life testing their resistances attained lows of 500 MΩ and 300 MΩ, respectively.

The technique of DC voltage conditioning with voltage reversal at severe conditions together with resistance measurements to ensure that the onset-of-degradation has not been exceeded, or only slightly exceeded, is recommended as a means of selecting capacitors for performance at less severe conditions of voltage and temperature for a specified term of time termed assured lifetime (ALT). The conditions of temperature, voltage and time for voltage conditioning and resistance measurements may be computed (Section 3.2.7).

3.5 Some Properties of Capacitors For Large-Scale Testing

Incorporated in this program is the requirement to determine failure rate as a function of voltage and temperature through large-scale life testing. From the data thus obtained, derating curves are to be derived and overall failure rates for operating conditions are to be estimated. The usefulness of procedures and methods for selecting reliable capacitors may be evaluated.

The capacitor designs selected for large-scale testing have capacitance of 0.01 μF and 0.033 μF, respectively. Construction is described in Section 3.1.

3.5.1 The 0.01 μF Capacitors

The 0.01 μF capacitors are identified as Lot No. 6S9205. A number of these capacitors were examined for electrical properties before the start of large-scale testing.

Charging currents at 25°C and 150°C are presented in Figures 84 and 85. Resistance vs time at 150°C is presented in Figure 86. Voltage reversal apparently effects rejuvenation of the capacitors (Figures 87 and 88). All these data are needed to establish selection conditions for ALT (Sections 3.2.7 and 3.4.5).

Steady-state Current-Voltage curves (Figure 89) being definitely non-ohmic indicate that time-to-onset-of-degradation for Lot 6S9205 capacitors occurs sooner than for other lots examined earlier in the course of this study and that the life test capability of this lot is inferior to earlier lots (Section 3.2.8). There is the indication (Figure 90) that the predominant failure mechanism will be "Schottky" type emission (Section 3.3).

3.5.2 The 0.033 μF Capacitors

The 0.033 μF capacitors are identified as Lot 6S11446. A sampling of these capacitors was completed before the entire lot was processed and electrical properties examined. Some of the properties

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are presented in Table IV. The time to onset-of-degradation for one of the worst capacitors was 55 hours at 150°C, 95 VDC. Using relationships presented earlier (Section 3.2.7), Lot 6S11446 might be screened to secure ALT's of 9500 hours at 25 VDC, 125°C or 27,000 hours at 50 VDC, 85°C.

A steady-state Current-Voltage plot (Figure 91) reveals near-ohmic conductivity over a considerable voltage range and prognosticates for long life (Section 3.2.8). "Schottky" type emission (Section 3.3) is not expected to be the principal failure mechanism over a considerable voltage range (Figure 92).

3.6 Completion of the Voltage/Temperature Life Test Matrix for 0.01 μF C67 Case Size I MONOLYTHIC Capacitors

3.6.1 Introduction

The 0.01 μF C67 Case Size I MONOLYTHIC capacitors were selected from Lot 6S9205. Figure 93 shows the life test schedule, including the preliminary two-step burn-in. Table V lists the voltage/temperature conditions for the matrix.

3.6.2 Burn-In and Life Test Failure Criteria

The leakage current data obtained from Steps A and B of the burn-in (Figure 93) were used to establish the following criteria which determined the short-lived capacitors on life test. A unit was short-lived or predicted to be a potential failure on life test if:

1. Its leakage current after 1, 50, 51, or 100 hours of burn-in exceeded 0.1 μA.

2. The ratio of the 50th to 1st hour leakage current of the burn-in exceeded 10.

3. The ratio of the 100th to the 51st hour leakage current of the burn-in exceeded 10.

On life test, a unit was considered a failure if its insulation resistance reading was 500 megohms or less.

3.6.3 Comparison of Units and Negative and Positive Potential

One half of the capacitors in each voltage/temperature group were life tested at negative potential as in Step B (Figure 93) of the burn-in because experience has shown that 50% of the units screened by the procedures in Steps A and B of the burn-in can expect placement

in a circuit whose applied DC voltage is negative. The readings of units with positive voltage were compared to units reading with negative voltage. There was no significant difference at the 99% confidence level between the means of the two populations. At the same level of confidence, there is no difference between the standard deviations of the two populations.

3.6.4 Leakage Current Histograms

Figures 94 through 105 are histograms of the leakage current data obtained after 10,000, 15,000, 20,000 and 25,000 hours of life testing. Although leakage currents of the devices at conditions in the matrix increased with time, capacitors in the three 150°C test conditions had significantly greater leakage current increases with time than those devices at the other test conditions. Not only do the histograms affirm that the units at the 150°C test conditions had greater leakage currents, but also affirm that the units degraded earlier on life test.

3.6.5 Assured Lifetimes

The assured lifetime (ALT) is the guaranteed period over which the capacitor can survive a given voltage/temperature condition.

The ALT values listed in Table VI were based on the burn-in conditions where:

Matrix 1

E_2 = 200 volts

T_2 = 423°K (150°C)

t_2 = 50 hours

and calculated using the following generalized equation:

$$t_1 = t_2 \left[\frac{E_2}{E_1}\right]^{2.7} \exp\left[\frac{0.90}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \qquad (14)$$

where:

t_1, t_2 = performance times under conditions 1 and 2, respectively

E_1, E_2 = volts/mil for conditions 1 or 2, respectively

k = Boltzmann's constant

T_1, T_2 = temperature conditions 1 and 2, respectively, degrees Kelvin

The assured lifetimes for the individual test conditions of the matrix are presented in column 3 of Table VI.

3.6.6 Results of Burn-In Selection Criteria

Of 1200 units placed on life test, 869 (72%) were predicted not to fail prior to ALT according to the burn-in failure criteria outlined in Paragraph 3.6.2. The remaining 331 (28%) were predicted to fail by the same criteria.

3.6.6.1 Performance of Units Predicted Not to Fail Prior to ALT

Of the 869 units not predicted to fail by the burn-in criteria, six did fail prior to the assured lifetimes as calculated in Paragraph 3.6.5. These six units can be considered as unanticipated failures. They account for 0.69% of the total units predicted not to fail. Thus there is a 99.31% probability that the units predicted not to fail by the burn-in criteria will remain as non-failures throughout the assured lifetime of the unit.

The unanticipated failures occurred at three of the ten voltage/temperature conditions as shown in Table VI.

Life testing for all cells was continued for 25000 hours. In some instances this duration considerably exceeded ALT and a significant number of failures occurred between ALT and 25000 hours. The data, summarized in Weibull probability plots, are presented in Figures 106 and 107.

3.6.6.2 Failure Rate of Units Predicted Not to Fail Prior to ALT

In order to evaluate the assured lifetime the failure rate calculations are based on the assured lifetime hours for each cell. Therefore only those failures that occurred prior to the

assured lifetime were used. The number of failures occurring prior to ALT are given in column 5 of Table VI. In comparison, the number of failures up to 25,000 hours is given in column 6 of Table VI. The value of the ALT calculations and the burn-in selection criteria is emphasized by the difference in the number of failures between the two columns. The ALT calculations do correctly select a useful life for the capacitors, which is demonstrated to be a function of voltage/temperature conditions.

To calculate a failure rate for the matrix, all voltage/temperature conditions were converted to the conditions of the capacitor (100 V/125°C). This was accomplished by the use of Equation (14) and using the 100V/125°C assured lifetime of 1557 hours as the performance time. For example, to obtain the equivalent of 100V/125°C from 200V/125°C, the following inputs would have to be made into Equation (13):

$E_2 = 200 \qquad E_1 = 100$

$T_2 = 398 \qquad T_1 = 398$

$t_2 = 240$ (ALT)

Solving for t_1, the equivalency factor for one unit would be 1536 hours. In cases where the assured lifetime is beyond the duration of the life test, the 25,000 hour end of test time is substituted for the ALT. The equivalency factors are given in column 7 of Table VI.

Equivalent unit hours to ALT are obtained by multiplying the equivalency factor for each cell by the number of units on test. Unit hours contributed by the capacitors failing prior to ALT are deleted from the calculations, since their unit hours would not appreciably change the failure rate.

Failure rate is calculated by use of the following equation:

$$\text{Failure Rate (\%/1000 hours)} = \left(\frac{f+1}{h}\right)\left(10^5\right)\left(\chi^2\right) \quad (15)$$

where:

f = number of failures

h = equivalent unit hours

χ^2 = chi square confidence factor*

The failure rate for the matrix at arbitrary conditions of 100V/125°C based on 1,163,395 unit hours and six failures is 0.89%/1000 hours at the 90% confidence level. At transistor circuitry conditions of 25V/125°C the failure rate drops to 0.021%/1000 hours.

Since military specifications for ceramic capacitors are geared to 125°C usage conditions, the failure rate for the matrix less 150°C cells (based on 837,000 unit hours and 2 failures) is 0.64%/1000 hours. At transistor circuitry conditions (25V/125°C) the failure rate is 0.015%/1000 hours.

3.6.6.3 Performance of Units Predicted to Fail

The 331 units predicted to fail can be broken down into two categories: those predicted to fail that did not fail (Table VII) and those predicted to fail that did fail (Table VIII).

Of 331 units, 175 did actually fail on life test. Of the 175, 62 failed before the assured lifetime (Table IX). This high number of failures prior to ALT is indicative of the number of units culled from matrix calculations of Paragraph 3.6.6.2. The burn-in selection criteria avoided these units being classified as units predicted not to fail.

3.7 Completion of Life Testing of the Voltage/Temperature Matrix for 0.033 μF, C67 Case Size I MONOLYTHIC Capacitors

3.7.1 Introduction

Testing of the 0.033 μF, C67 Case Size I MONOLYTHIC capacitors (Lot 6S 11446) constructed with stacked ceramic dielectric layers 0.001 inches thick, was in accordance with the test schedule, which included the two-step burn-in (Figure 108). Table X lists the life test conditions.

---

*χ^2 value is a function of f, e.g., at 90% confidence level where: $f = 0$, $\chi^2 = 2.30$, ; $f = 6$, $\chi^2 = 1.51$

3.7.2 Burn-In and Life Test Criteria (Figure 108)

The leakage current data obtained from Steps A and B of the burn-in were used to establish the following criteria which determined the short lived capacitors on life test. A unit was short lived or a potential failure on life test if:

1. Its leakage current after 1, 24, 25 or 48 hours of burn-in exceeded 0.1 µA.

2. The ratio of the 24th to the 1st hour leakage currents was less than 0.2 or exceeded 5.

3. The ratio of the 48th to the 25th hour leakage currents was less than 0.2 or exceeded 5.

On life test, a unit was considered a failure if its insulation resistance reading was 500 megohms or less.

3.7.3 Comparison of Units at Negative and Positive Potential

One half of the capacitors in each voltage/temperature group were life tested at negative potential as in Step B of the burn-in since experience has shown that 50% of the units screened by the procedures in Steps A and B of the burn-in can expect placement in a circuit whose applied DC voltage is negative. The readings of the units at positive voltage were compared to the readings of the units at negative voltage. There was no significant difference at the 99% confidence level between the means of the two populations. At the same level of confidence there is no difference between the standard deviations of the two populations.

3.7.4 Leakage Current Histograms

Figures 109-111 are histograms of the leakage current data obtained after 10,000 hours of life testing. As in the life testing of 0.01 µF capacitors, the three 150°C conditions displayed significantly greater leakage current increases with time than for devices at the other test conditions.

3.7.5 Assured Lifetimes

The ALT values listed in Table XI are based on the burn-in conditions where:

$E_2 = 100$ V

$T_2 = 423°K$ (150°C)

t_2 = 24 hours

and calculated using Equation (14).

3.7.6 Failure Prediction

Of 1200 units placed on life test, 1149 (96%) were predicted not to fail prior to ALT according to the burn-in failure criteria outlined in Paragraph 3.7.2. The remaining 51 (4%) were predicted to fail by the same criteria.

3.7.6.1 Performance of Units Predicted Not to Fail Prior to ALT

Of the 1149 units predicted not to fail by the burn-in criteria, none failed prior to the assured lifetimes or 10,000 hours, whichever occurred first, as calculated in Paragraph 3.7.5 (Table XI). There were no unanticipated failures.

In certain test cells, the duration of testing considerably exceeded ALT and a significant number of failures occurred between ALT and 10,000 hours. The data are summarized in Weibull Probability plots (Figures 112 and 113).

3.7.6.2 Failure Rate Calculations

As in Paragraph 3.6.6.2, the failure rate calculations are based on the assured lifetimes for each cell. Only those failures that occurred prior to the assured lifetime were used. In contrast to the lack of failures prior to ALT, column 6 of Table XI shows the distribution of failures up to 10,000 hours, which is beyond some ALT test conditions. As in the 0.01 µF matrix, the ALT calculations correctly select a useful life for the capacitors which is a function of voltage/temperature conditions.

The voltage/temperature conditions were converted to 25V/125°C by use of Equation (14) and the methodology described in Paragraph 3.6.6.2.

Equivalent unit hours to ALT are obtained by multiplying the equivalency factor for 25V/125°C by the number of units on test.

The failure rate is calculated by the use of Equation (15).

The failure rate for the 0.033 μF matrix at conditions of 25V/125°C is 0.086%/1000 hours with 90% confidence (Table XI). This failure rate is based on no failures and is restricted from being any lower by the number of available unit hours.

The failure rate for the matrix, less 150°C conditions, is based on 3,108,537 unit hours and no failures. But because of a decrease in unit hours the failure rate actually goes up to 0.12%/1000 hours, since the number of unit hours is reduced while f (Equation (15)) cannot be reduced below zero.

3.7.6.3 Performance of Units Predicted to Fail

The 51 units predicted to fail can be broken down into two categories; those predicted to fail that did not fail (Table XII) and those predicted to fail that did fail (Table XIII).

Of the 51 units, 25 did actually fail on life test. Of the 25, eight failed before the assured lifetime (Table XIV). These units have, in effect, been sorted out of the units not predicted to fail category by the burn-in selection criteria. Failure rate was 8.8% per 1000 hours at 25V/125°C.

3.8 Nomographic Reliability Evaluation of Ceramic Capacitors

An extensive matrix evaluation study has been completed on barium titanate ceramic monolithic capacitors. This material is universally used for high capacitance subminiature ceramic capacitors. The study has provided an acceleration equation for use in the rapid evaluation of these type parts. The acceleration equation is:

$$\text{Acceleration factor} = \frac{t_1}{t_2} = \left(\frac{E_2}{E_1}\right)^N \exp\left[\frac{W}{K}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] \quad (16)$$

where:

t_1 = time to start of degradation under use condition

t_2 = time to start of degradation under test condition

E_1 = voltage applied under use condition

E_2 = voltage applied under test condition

T_1 = temperature at use condition (°K)

T_2 = temperature at test condition (°K)

N = 2.7

W = 0.9 eV

K = 8.62×10^{-5} eV/°K

This acceleration equation has been converted to a nomogram for ease of use. The nomogram is shown in Figure 114. The following steps outline the use of this nomogram:

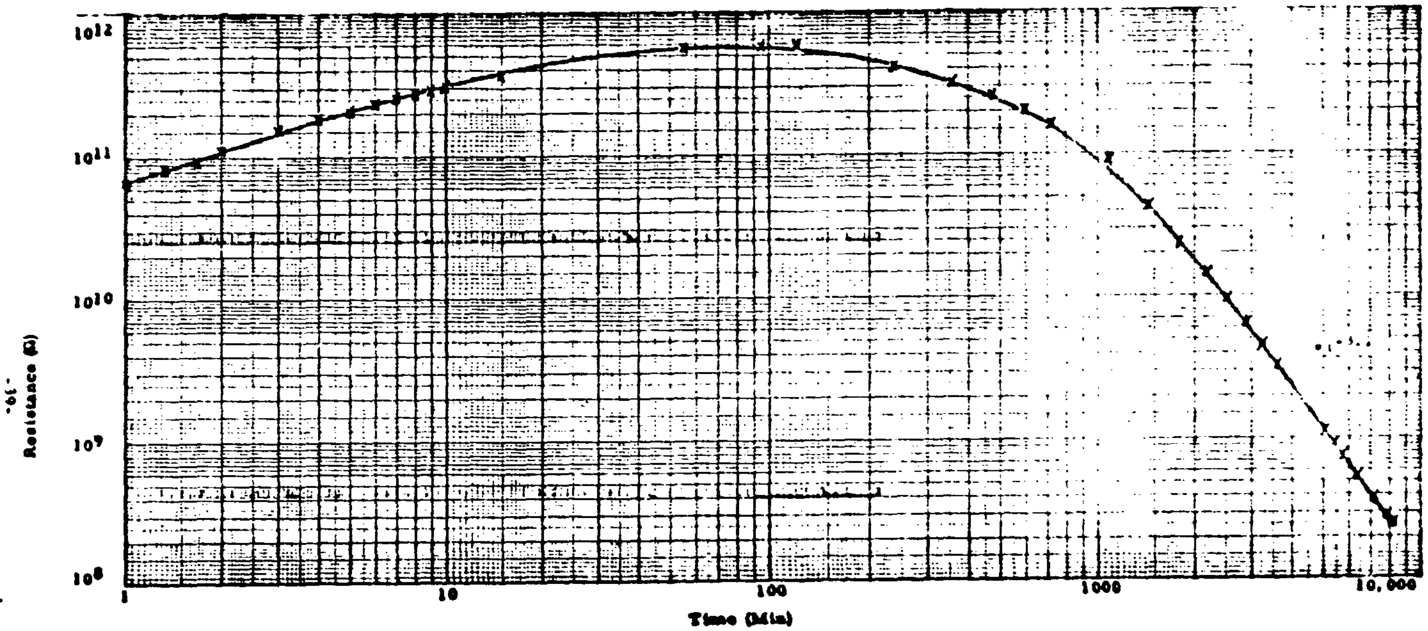
1. Locate the use temperature on scale T_1 (°C).

2. Locate the test temperature on scale T_2 (°C).

3. Place a straightedge across the use temperature on T_1 and the test temperature on T_2. This will determine a point on the line marked "Reference."

4. Determine the ratio of test voltage to use voltage, E_2/E_1. Locate this ratio on the E_2/E_1 scale.

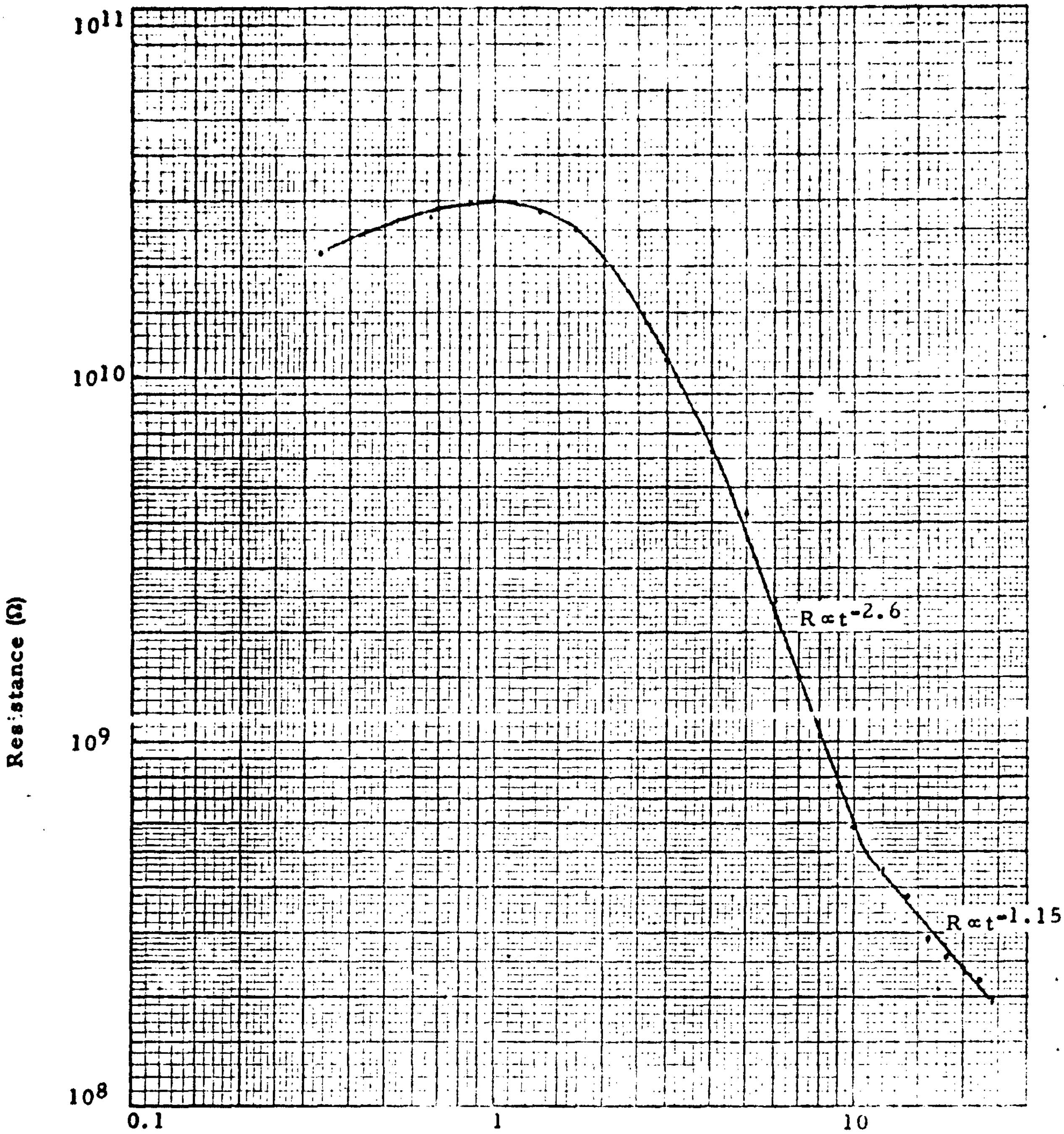
5. Place a straightedge across the E_2/E_1 scale at the ratio determined in Step 4 and the "Reference" point determined in Step 3. The intersection of the straightedge on "Acceleration Factor" line will determine the acceleration factor for testing compared to the use conditions.



RESISTANCE VS TIME
FOR A C67 CASE SIZE I MONOLYTHIC CAPACITOR (~8000 μμF)

Charge Condition: 90 VDC, 150°C
Dielectric Thickness: 0.0025 in.

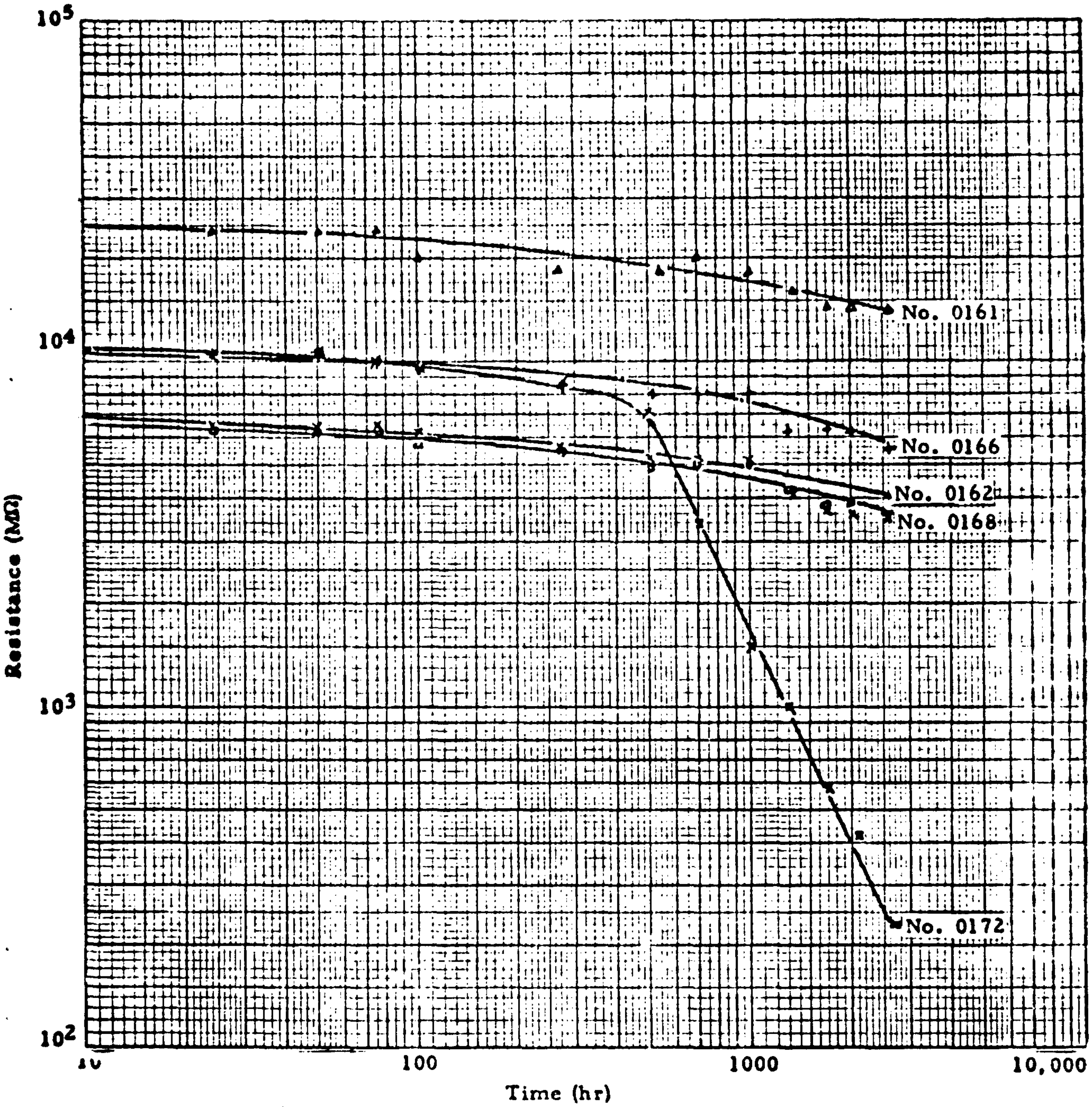
Figure 1



RESISTANCE VS TIME
FOR A C67 CASE SIZE I MONOLYTHIC CAPACITOR ([illegible] µµF)

Charge Condition: 90 VDC, 150 C
Dielectric Thickness: 0.0025 in.

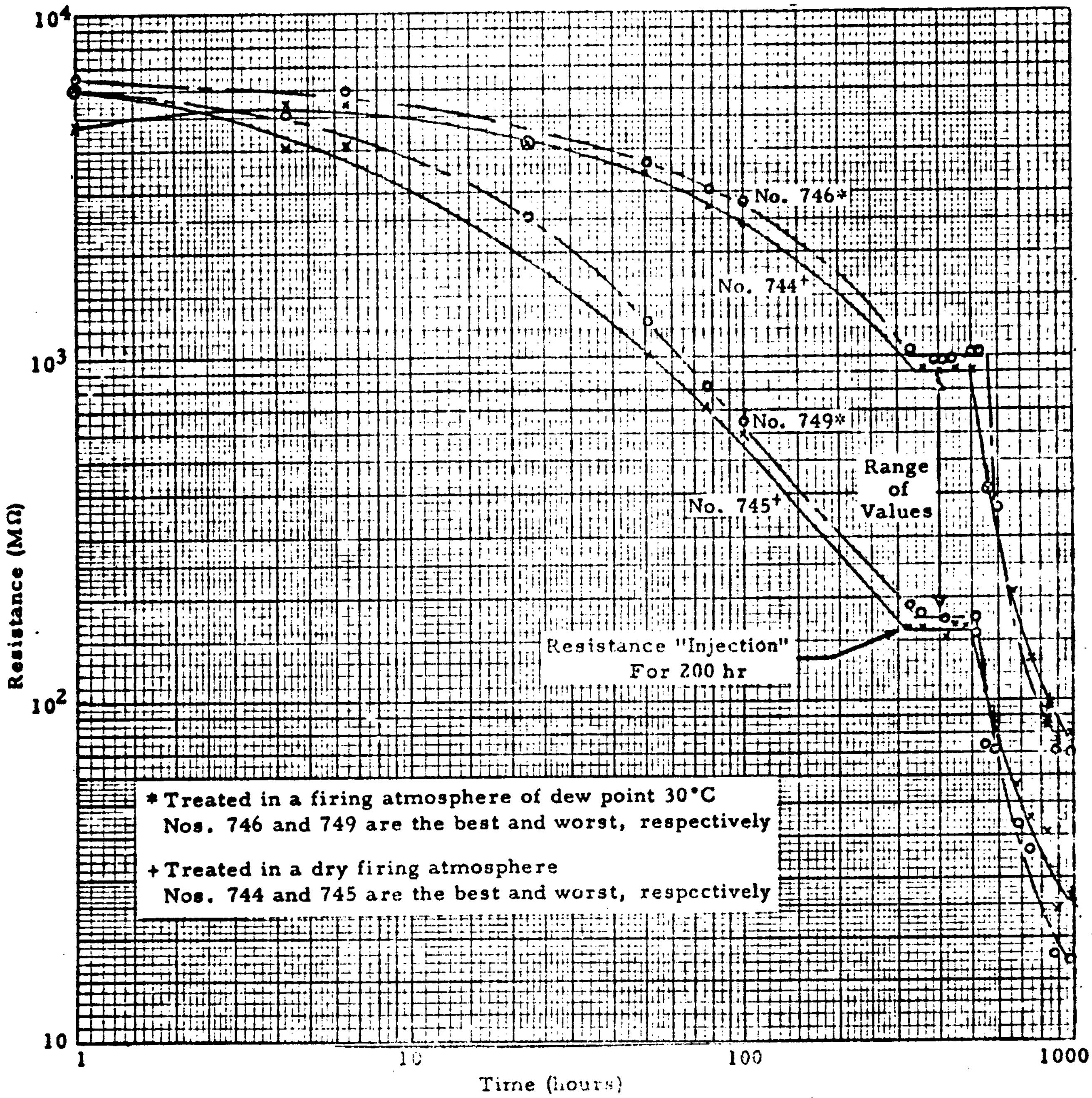
Figure 2



RESISTANCE VS TIME
FOR IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS

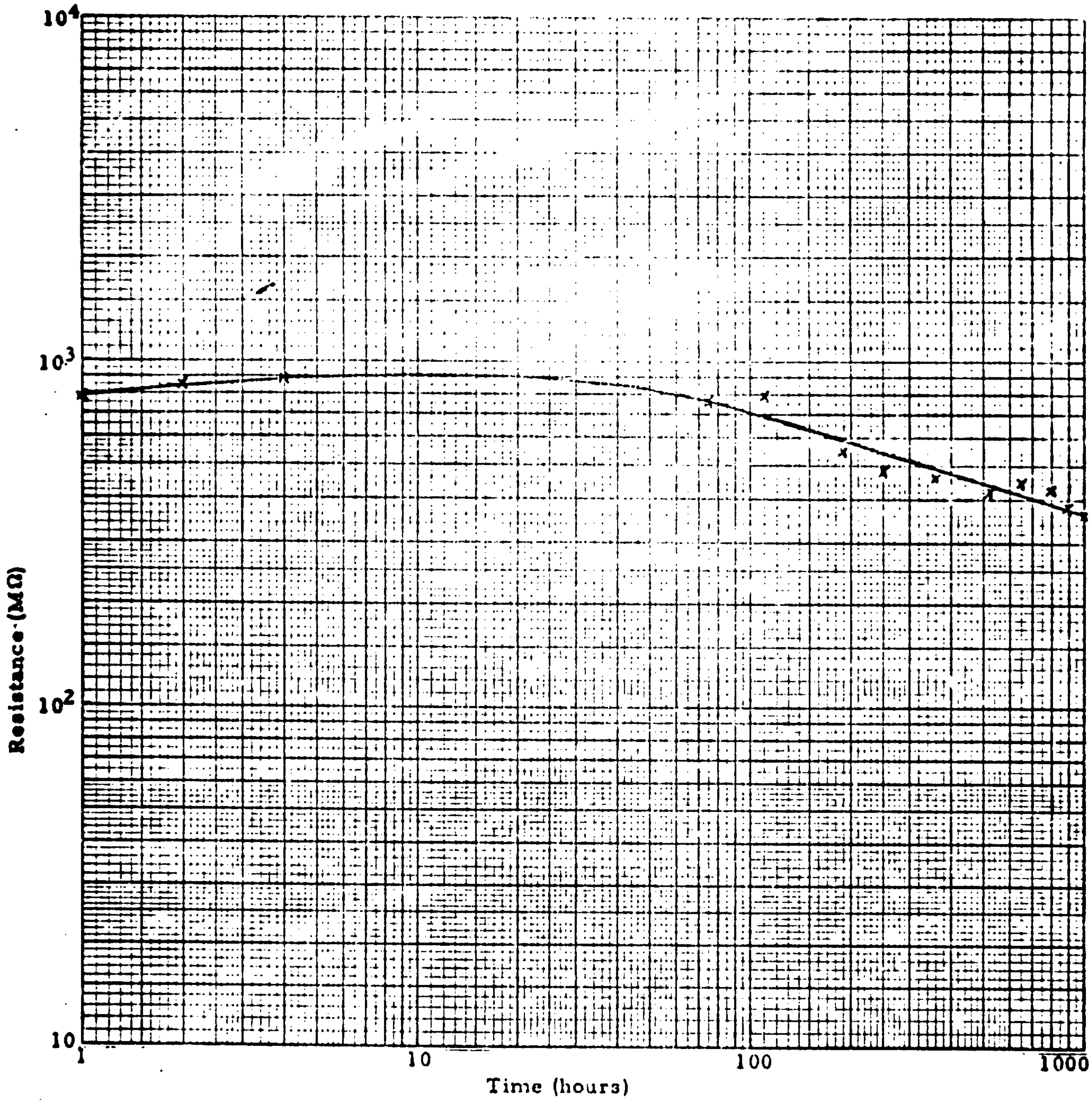
Dielectric Thickness: 0.0025 in.
Conditions: 150°C, 220 VDC

Figure 8



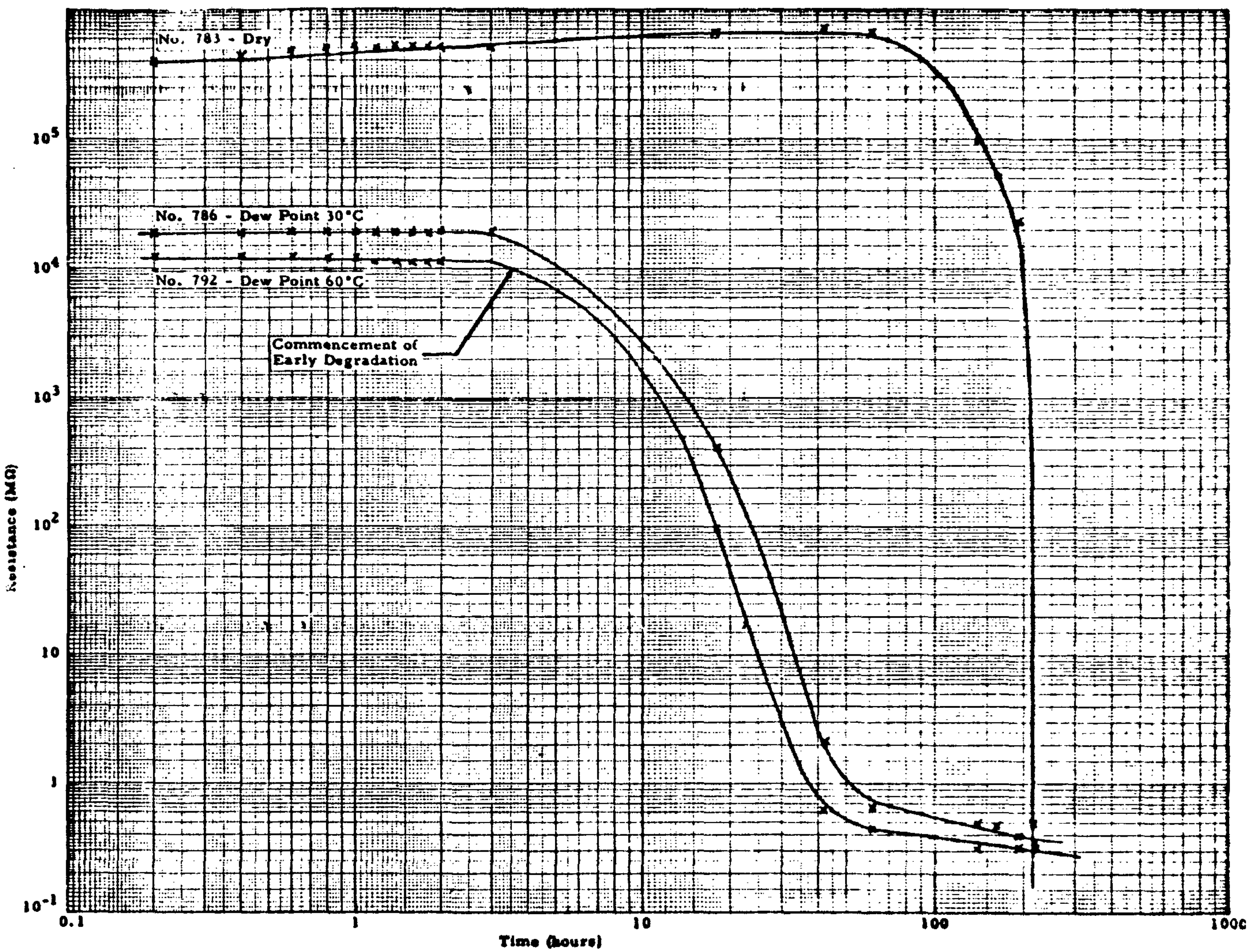
RESISTANCE VS TIME AT 149°C, [illegible] VDC (74 V/mil)
FOR POST-FIRING TREATMENTS
TO 0.14 μF C67 MONOLYTHIC CAPACITORS (Lot X905A)

Figure 4



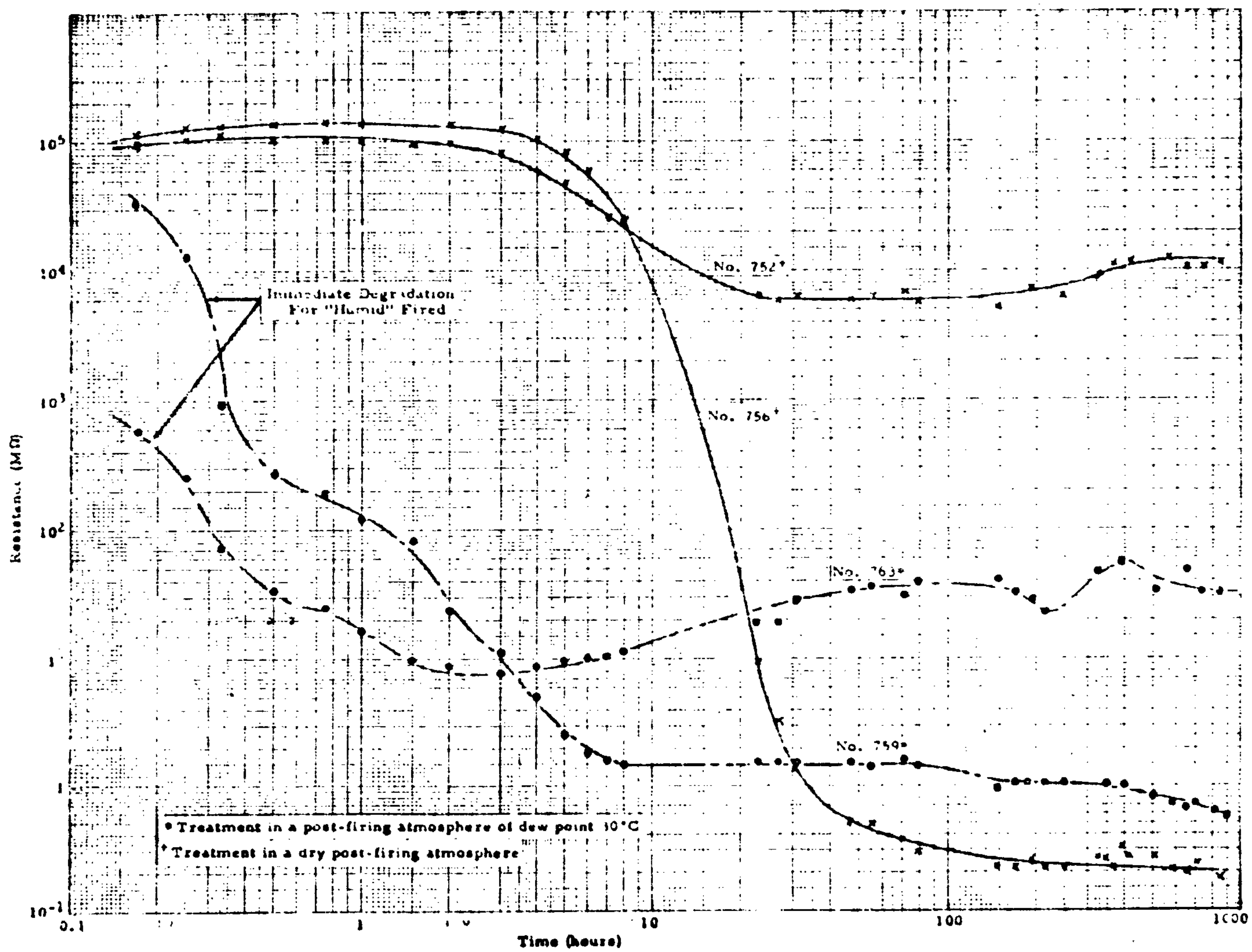
AVERAGE RESISTANCE VS TIME AT 149°C, 185 VDC (74 V/mil)
FOR POST-FIRING TREATMENTS
TO 0.08 μF C67 MONOLYTHIC CAPACITORS (Lot X901B)
(Data points are identical for capacitors refired
in dry air or humid air with dew point = 30°C)

Figure 5



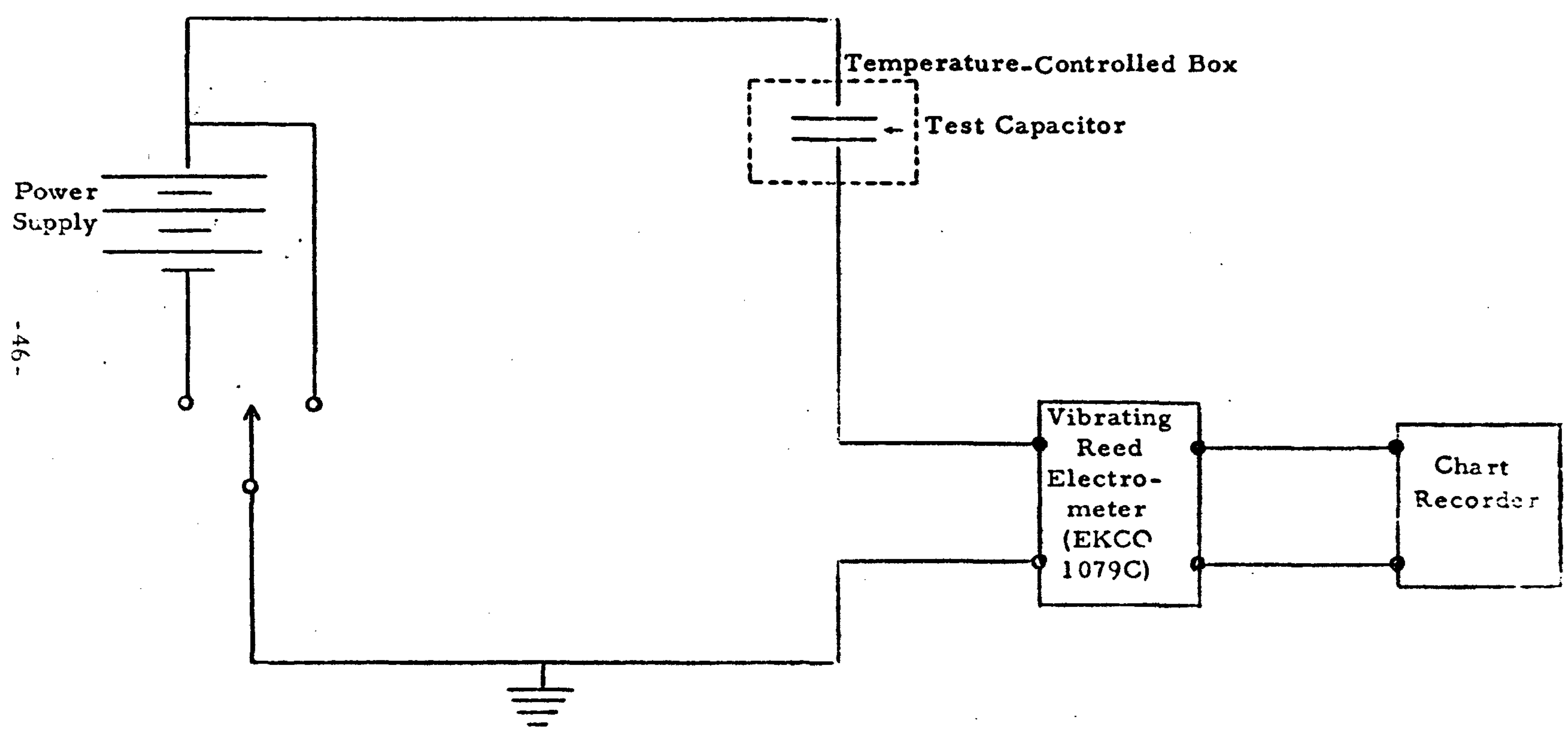
RESISTANCE VS TIME AT 149°C, 1000 VDC (45 V/mil)
FOR REFIRED DISCS OF K=40 NO30 TCC CERAMIC FABRICATED UNDER DRY AND HUMID AIR CONDITIONS

Figure 6



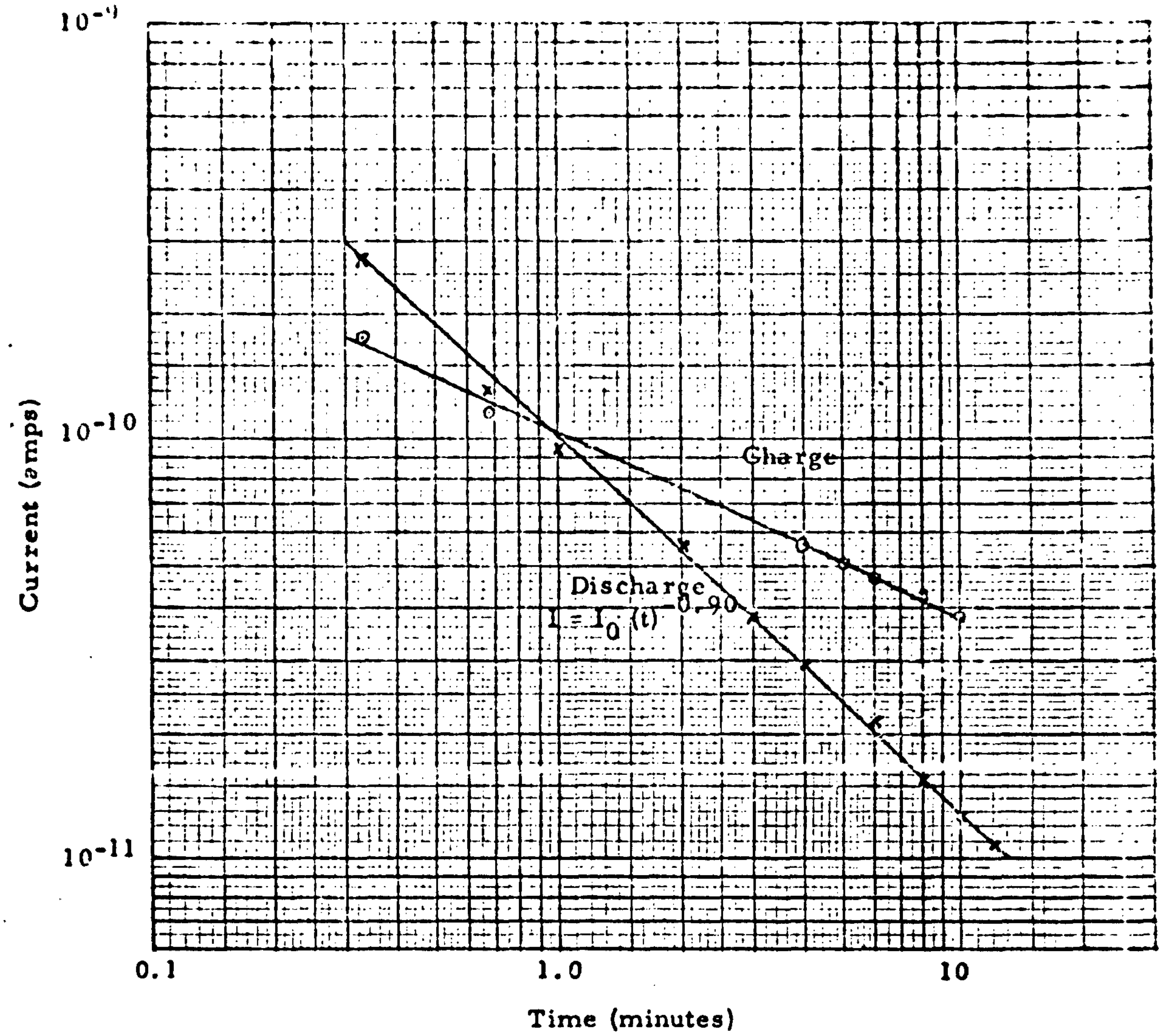
RESISTANCE VS TIME AT 150°C, 195 VDC (78 V/mil)
FOR REFIRED 0.0005 µF MONOLYTHIC CAPACITORS MADE FROM K = 40 NO30 TCC CERAMIC UNDER DRY AND HUMID AIR CONDITIONS

Figure 7



CIRCUIT USED FOR MEASURING CHARGE AND DISCHARGE CURRENT OF C67 CASE SIZE I MONOLYTHIC CAPACITORS

Figure 8

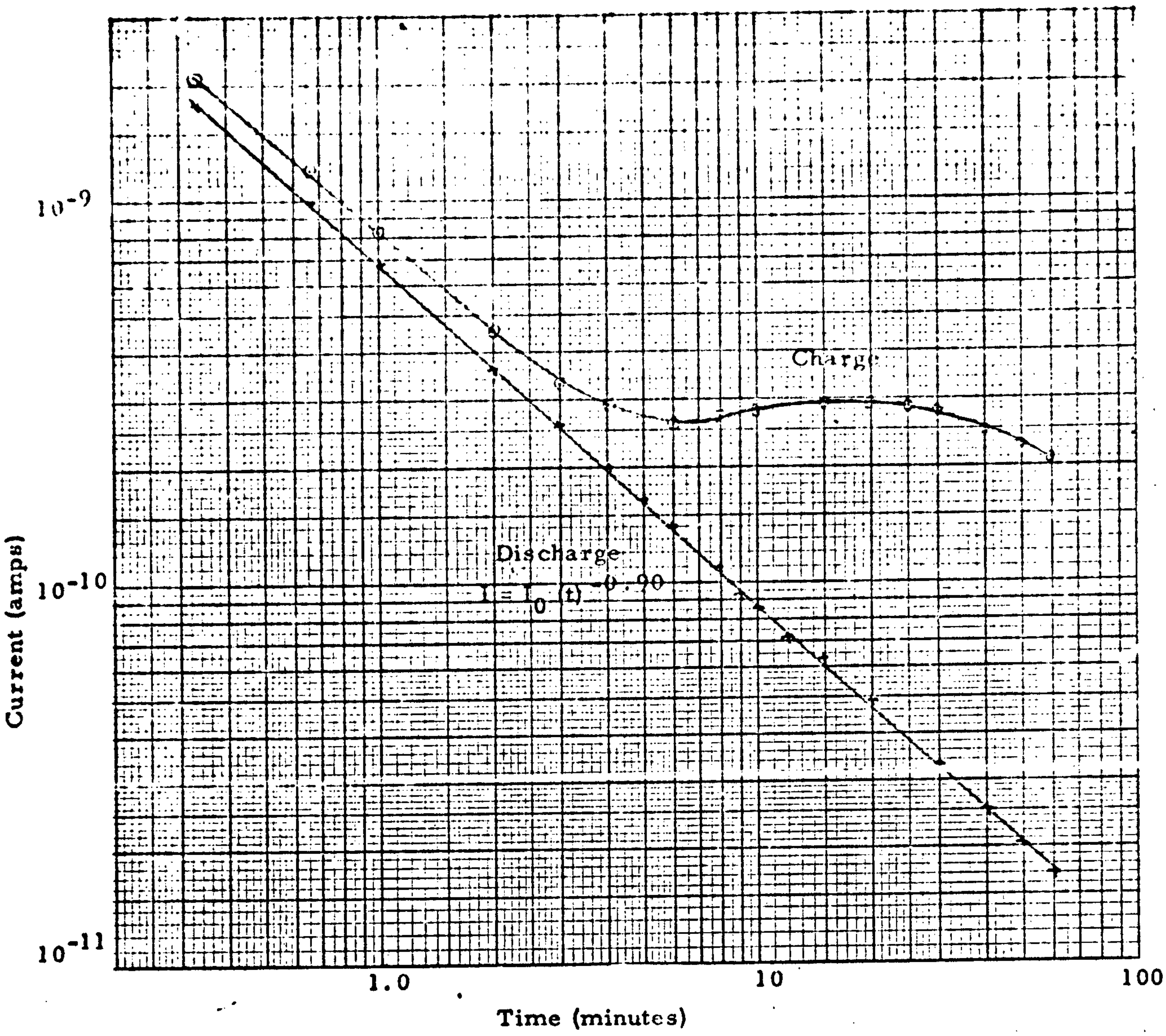


Charge Conditions: 225 VDC (90 V/mil), 25°C
Discharge Conditions: 25°C

Graph Showing

CHARGE AND DISCHARGE CURRENTS
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITOR (≅6000 μμF)

Figure 9

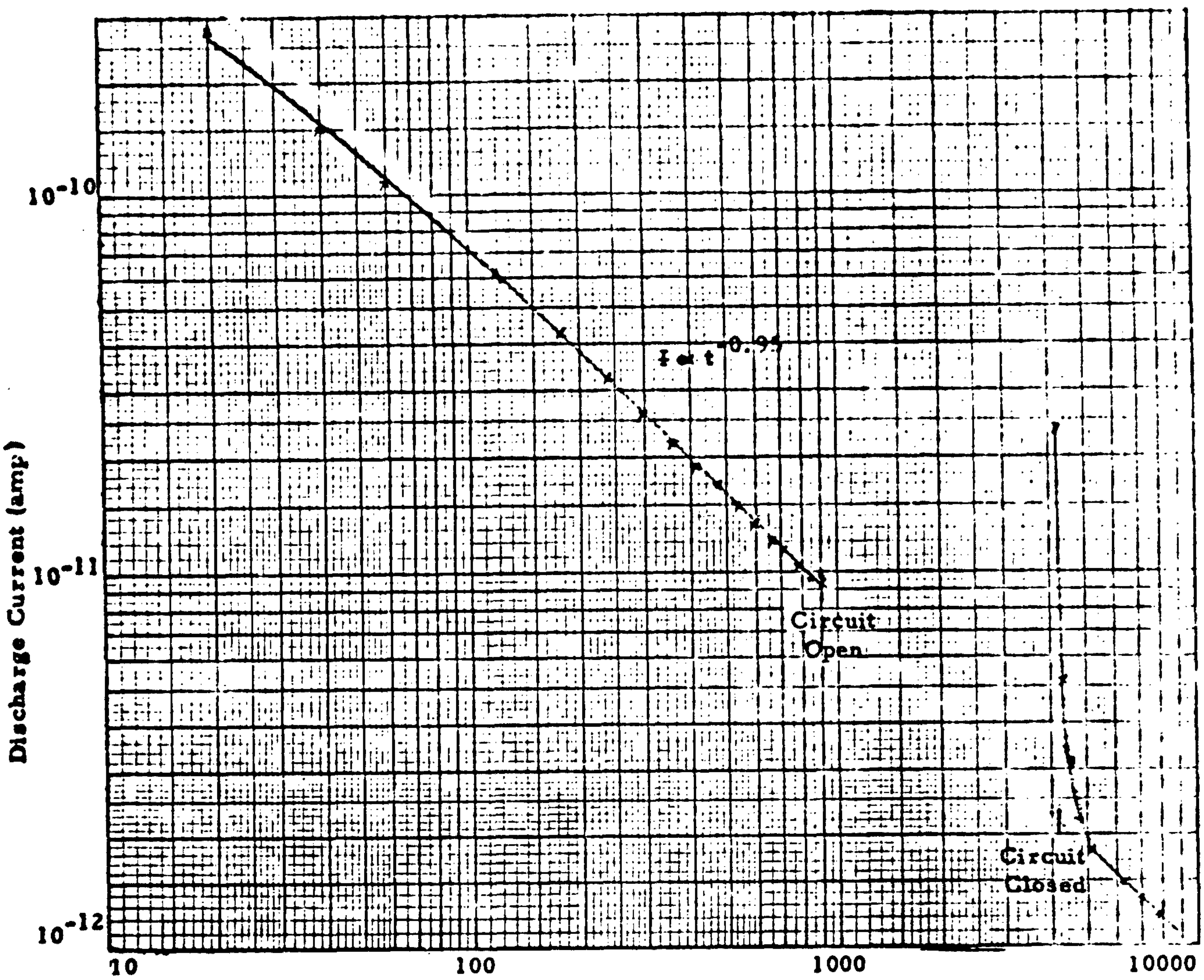


Charge Conditions: 225 VDC (90 V/mil), 150°C
Discharge Conditions: 150°C

Graph Showing

CHARGE AND DISCHARGE CURRENTS
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITOR (≅6000 μμF)

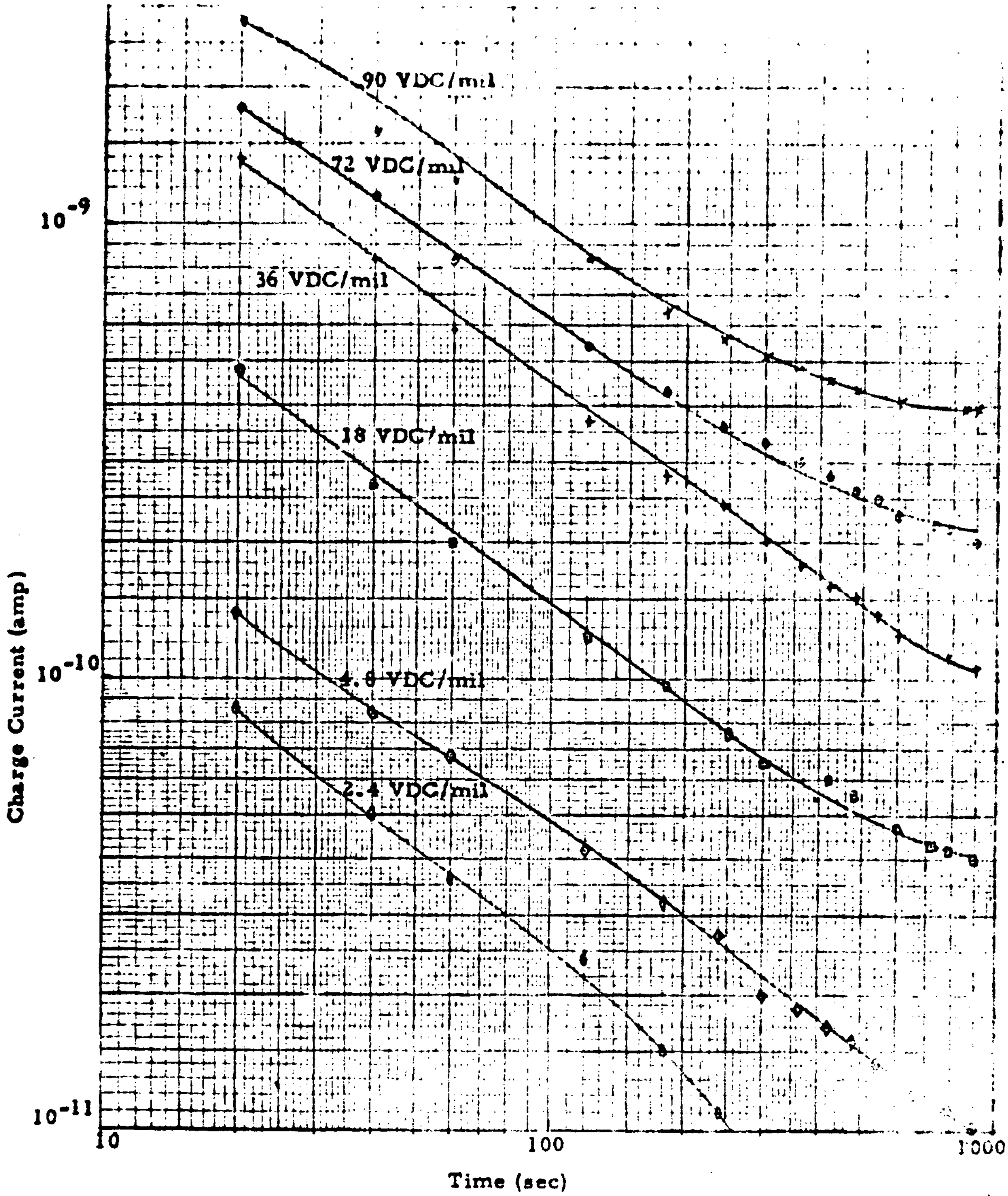
Figure 10



DISCHARGE CURRENT
FOR
A C67 CASE SIZE 1 MONOLYTHIC CAPACITOR (~6000 $\mu\mu$F)
(Charge conditions: 225 VDC, 1 hr, 28°C)

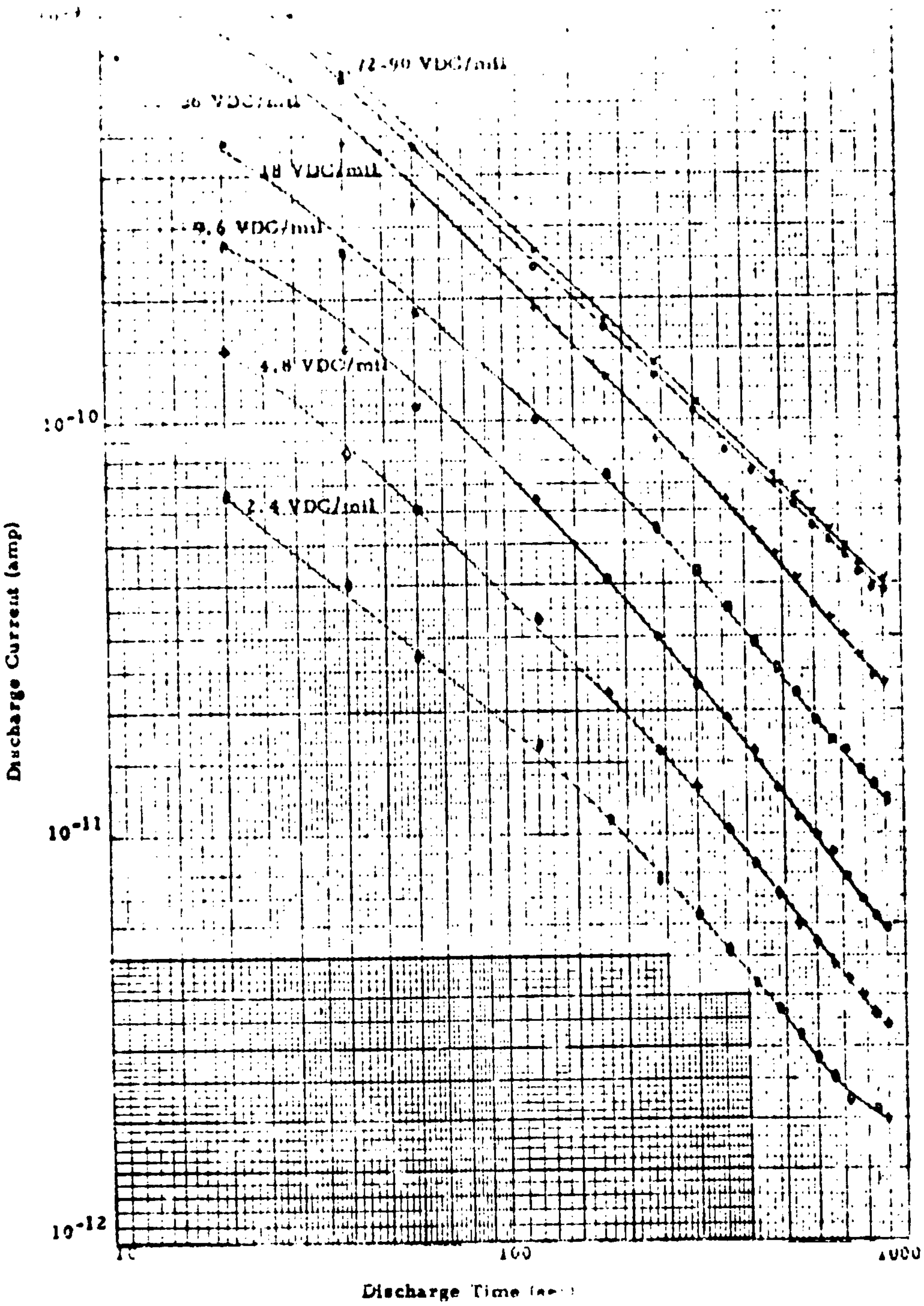
(Explanation of Graph: This graph shows discharge current vs time from initial discharge. After 15 min. continuous discharge the discharge circuit was opened for [illegible], after which it was closed again and the discharge continued.)

Figure 11



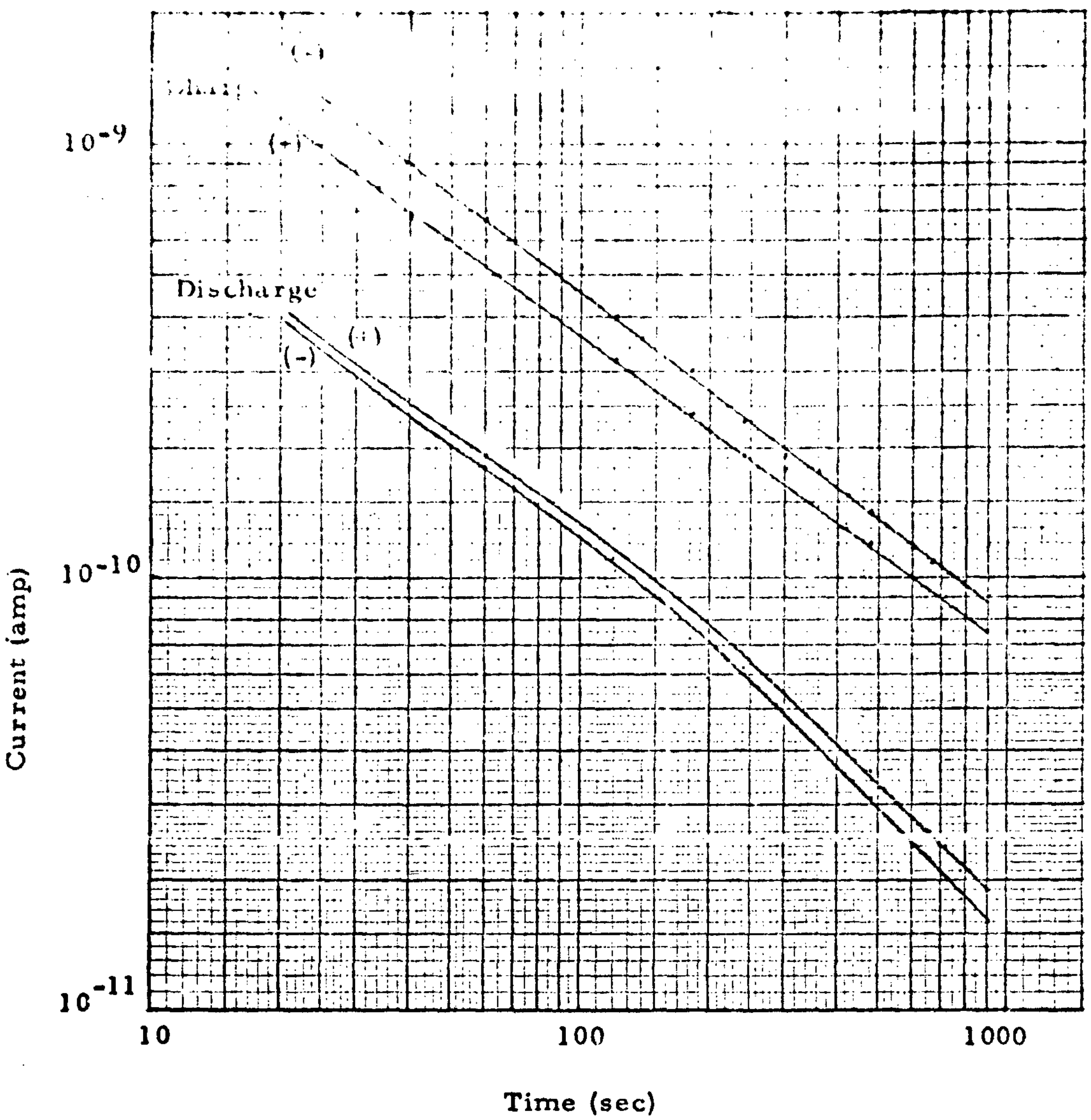
CHARGE CURRENT VS TIME
FOR C67 CASE [illegible] I MONOLYTHIC CAPACITORS (~6000 μμF)
(Charge conditions: 2.4-90 VDC/mil, 150°C)
(Dielectric Thickness: 0.0025 in.)

Figure 12



DISCHARGE CURRENT VS TIME
FOR
C57 CASE SIZE I MONOLYTHIC CAPACITORS
(Charge condition: 2.4-90 VDC/mil, 15 min, 150°C)

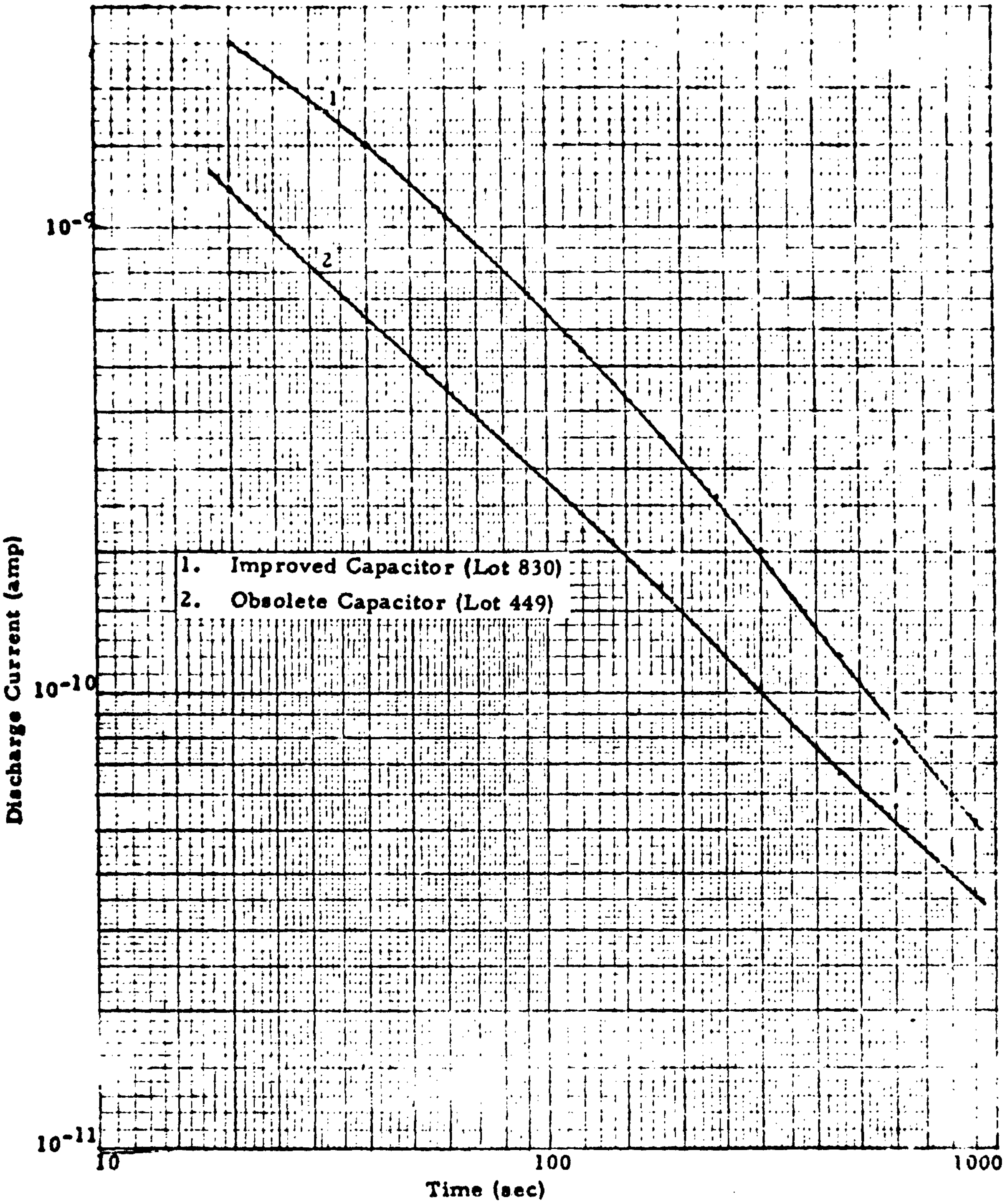
Figure 13



CHARGE AND DISCHARGE CURRENT CURVES
FOR
A FRESH C67 CASE SIZE I MONOLYTHIC CAPACITOR (~6000 μμF)

(This unit was charged in one direction (+) and discharged, then recharged in the reverse direction (-) and discharged; charge conditions: 225 VDC, 100°C)

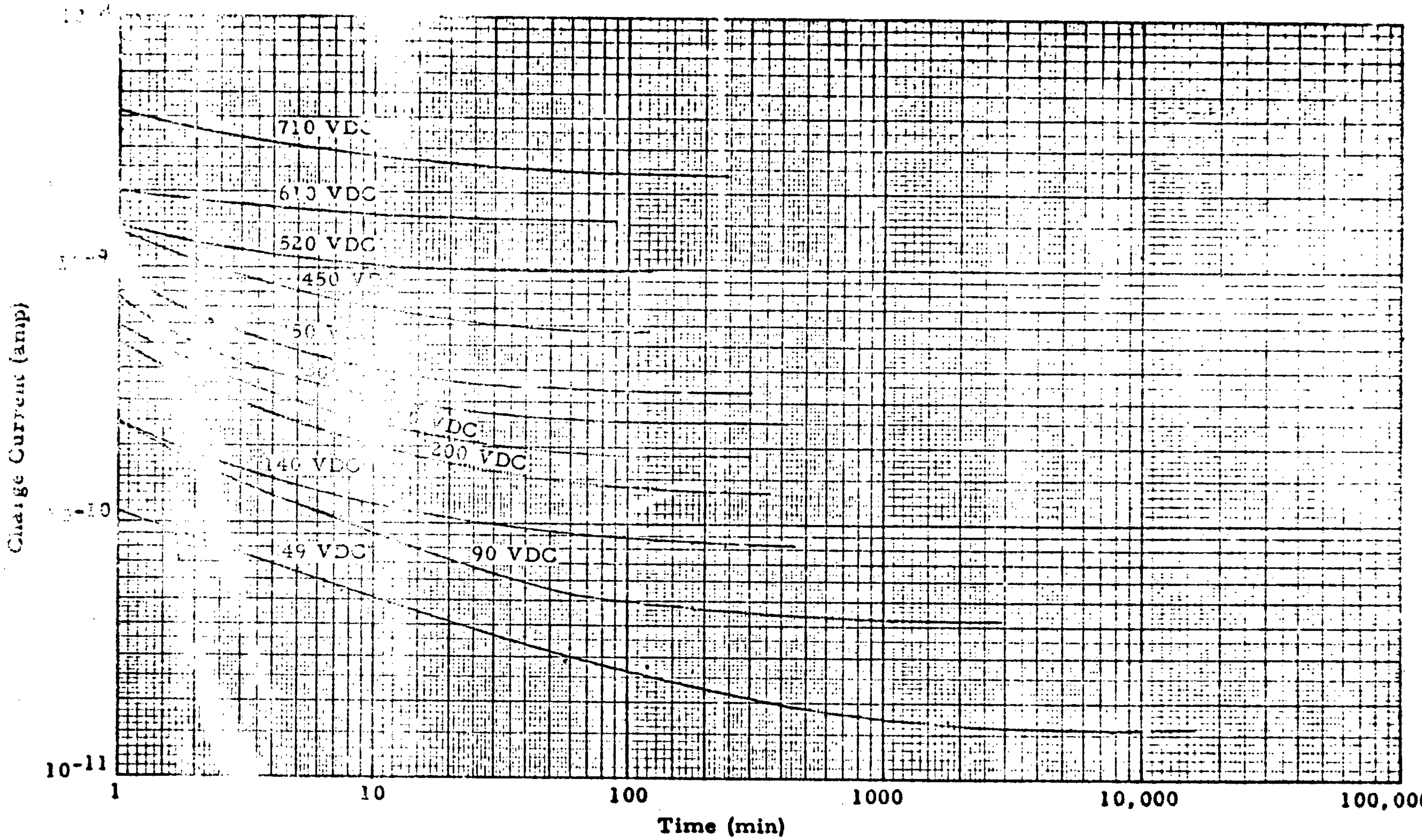
Figure 14



DISCHARGE CURRENT ... TIME AT 15...
FOR 0.01 μF C67 CAS... MONOLYTHIC CAPACITORS

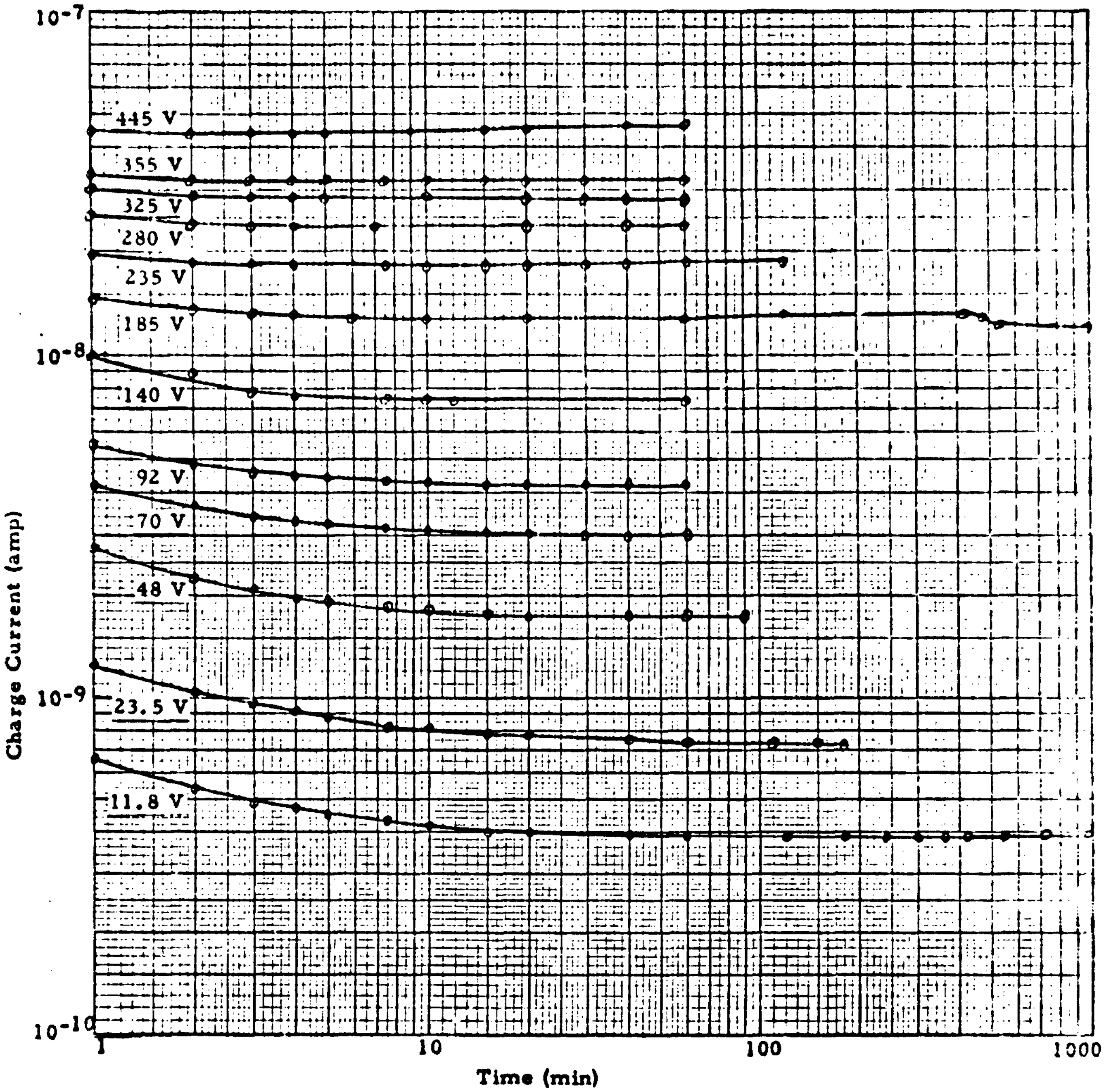
Charge Conditions: 93 VDC, 150°C for 15 min.
Dielectric Thickness: 0.0025 in.

Figure 15



CHARGE CURRENT VS TIME AT 85°C
FOR A NEW, IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITOR (Lot 830)
Dielectric Thickness: 0.0025 in.

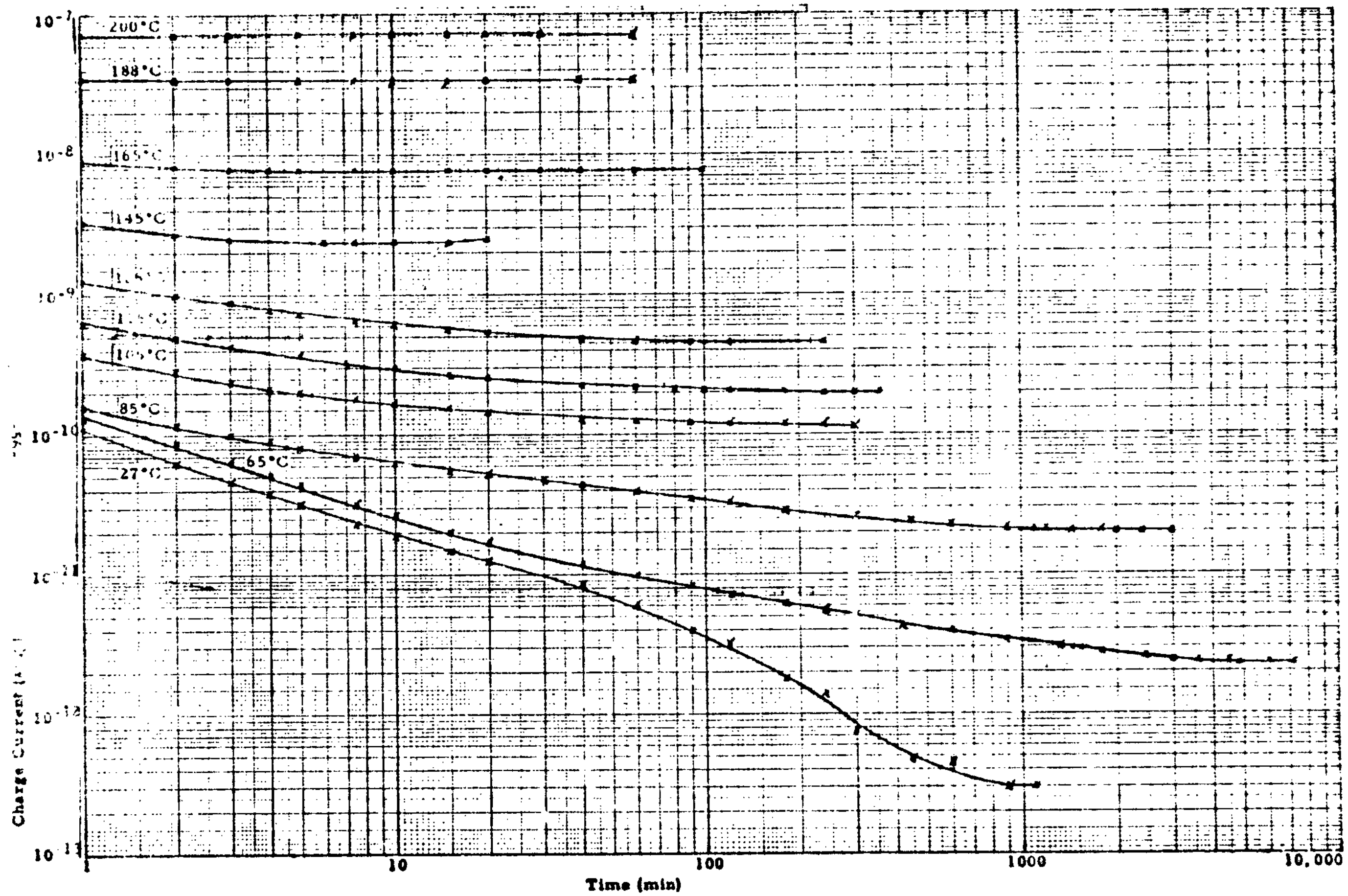
Figure 16



CHARGE CURRENT VS TIME AT 150°C
FOR AN IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITOR (Lot 83.)

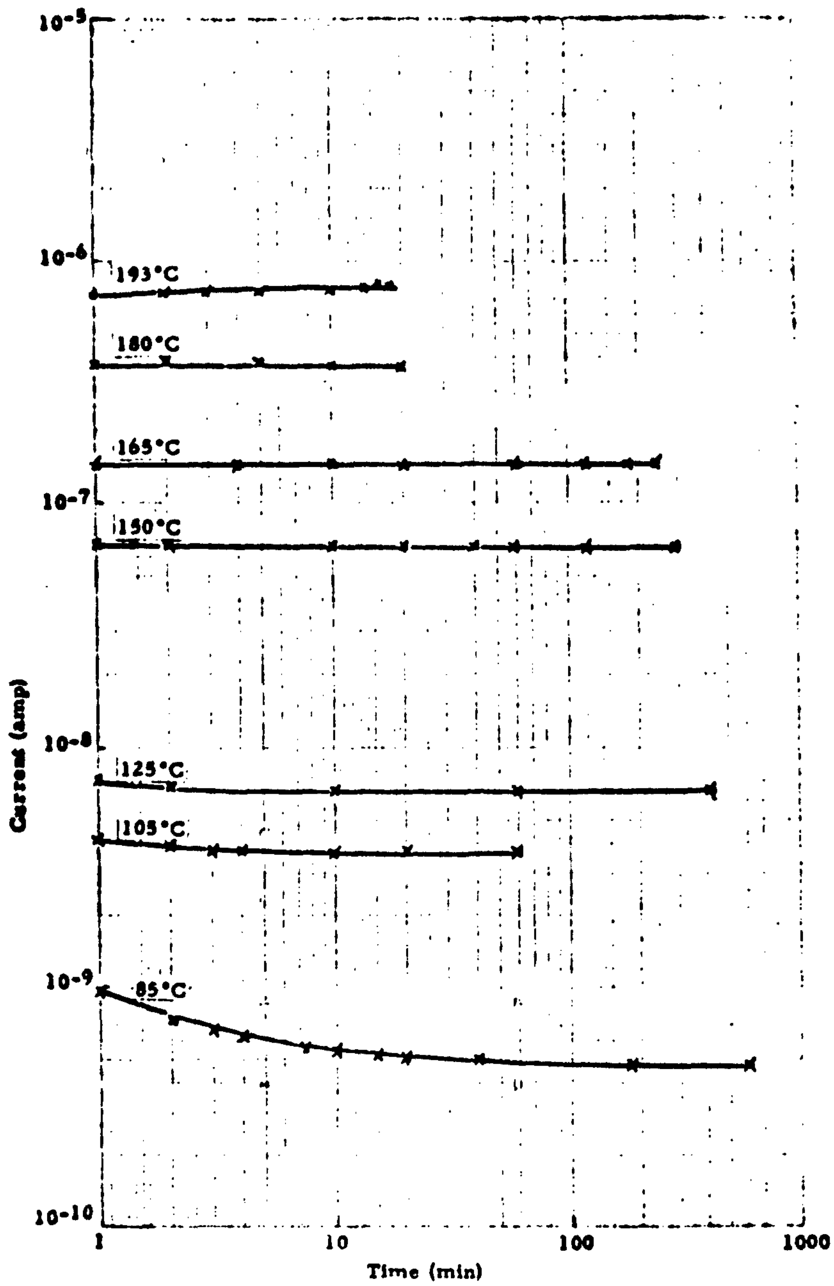
(Dielectric thickness in this capacitor is 0.0025 in.)

Figure 17



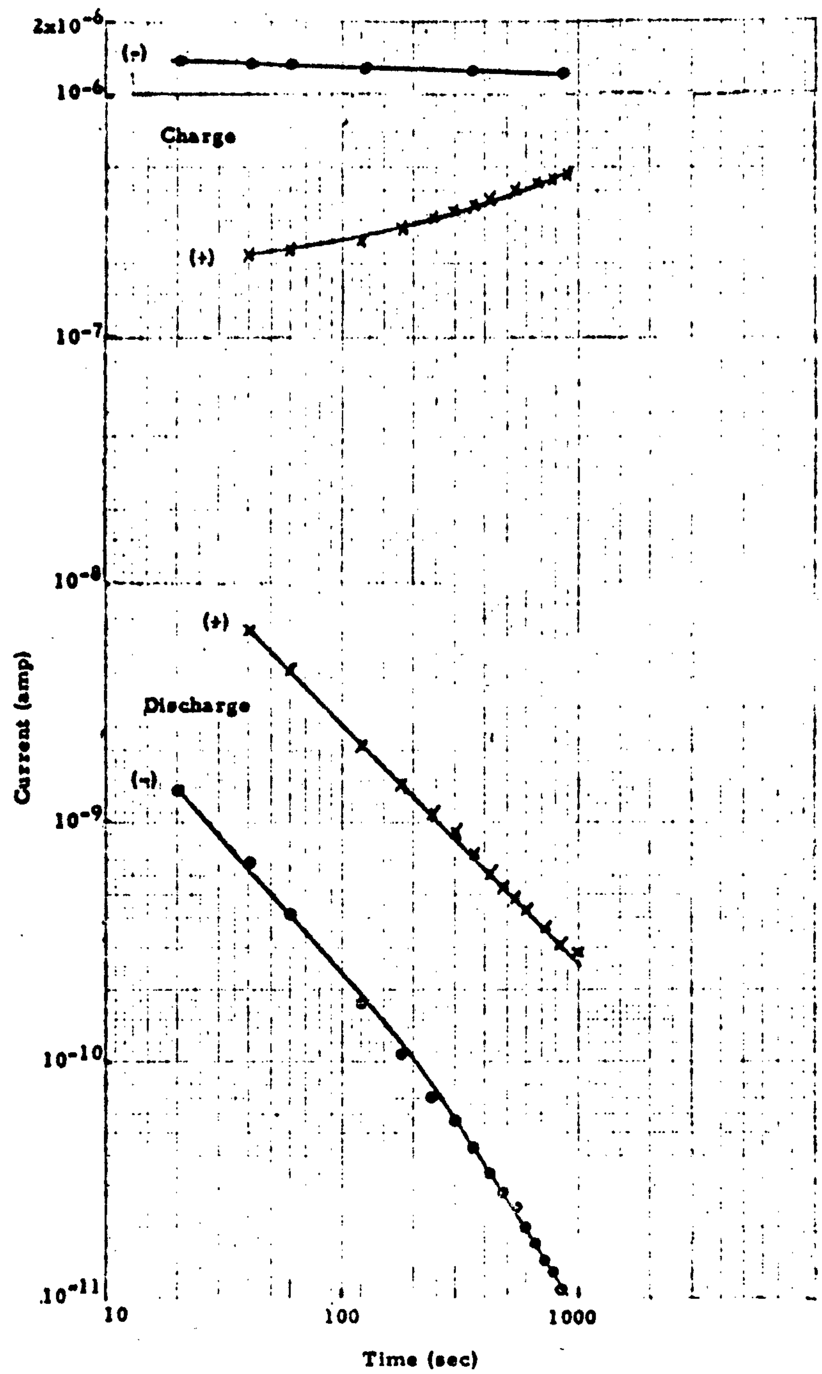
CHARGE CURRENT AT 93 VDC VS TIME
FOR AN IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITOR (Lot 830)

Figure 18



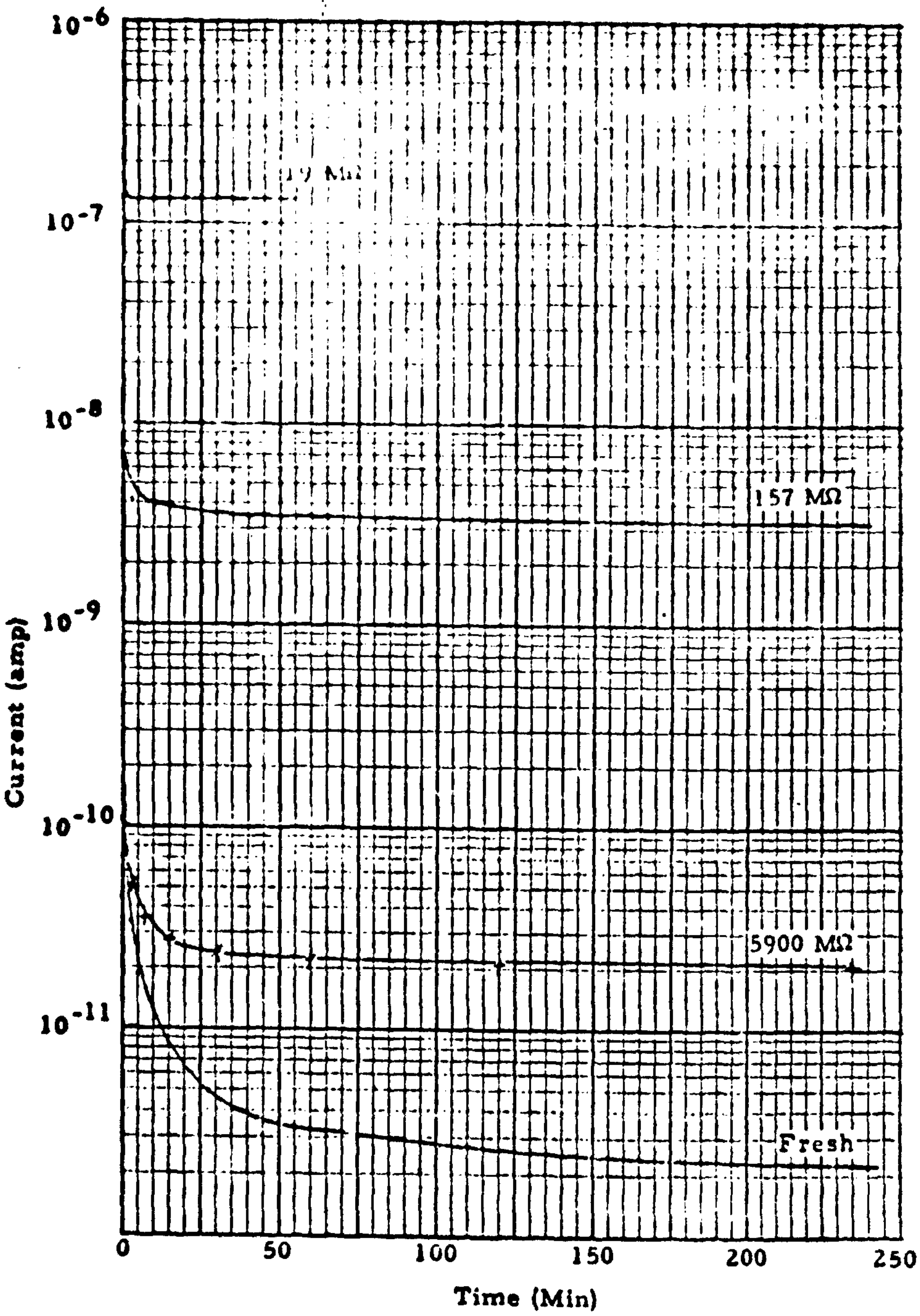
CURRENT VS TIME AT 200 VDC
FOR A NEW, IMPROVED 0.01 μF C67 CASE SIZE I
MONOLYTHIC CAPACITOR (Lot 830)

Figure 19



CHARGE AND DISCHA[illegible] [illegible]RENT CURVE[illegible]
FOR A DEGRADED [illegible] MONOLYTHIC CA[illegible]TOR (~4000 [illegible]F)
(This unit was charged in one direction (+) and discharged,
then recharged in the reverse direction (-) and discharged;
charge conditions: 225 VDC, 100°C)
Dielectric Thickness: 0.0025 in.

Figure 20

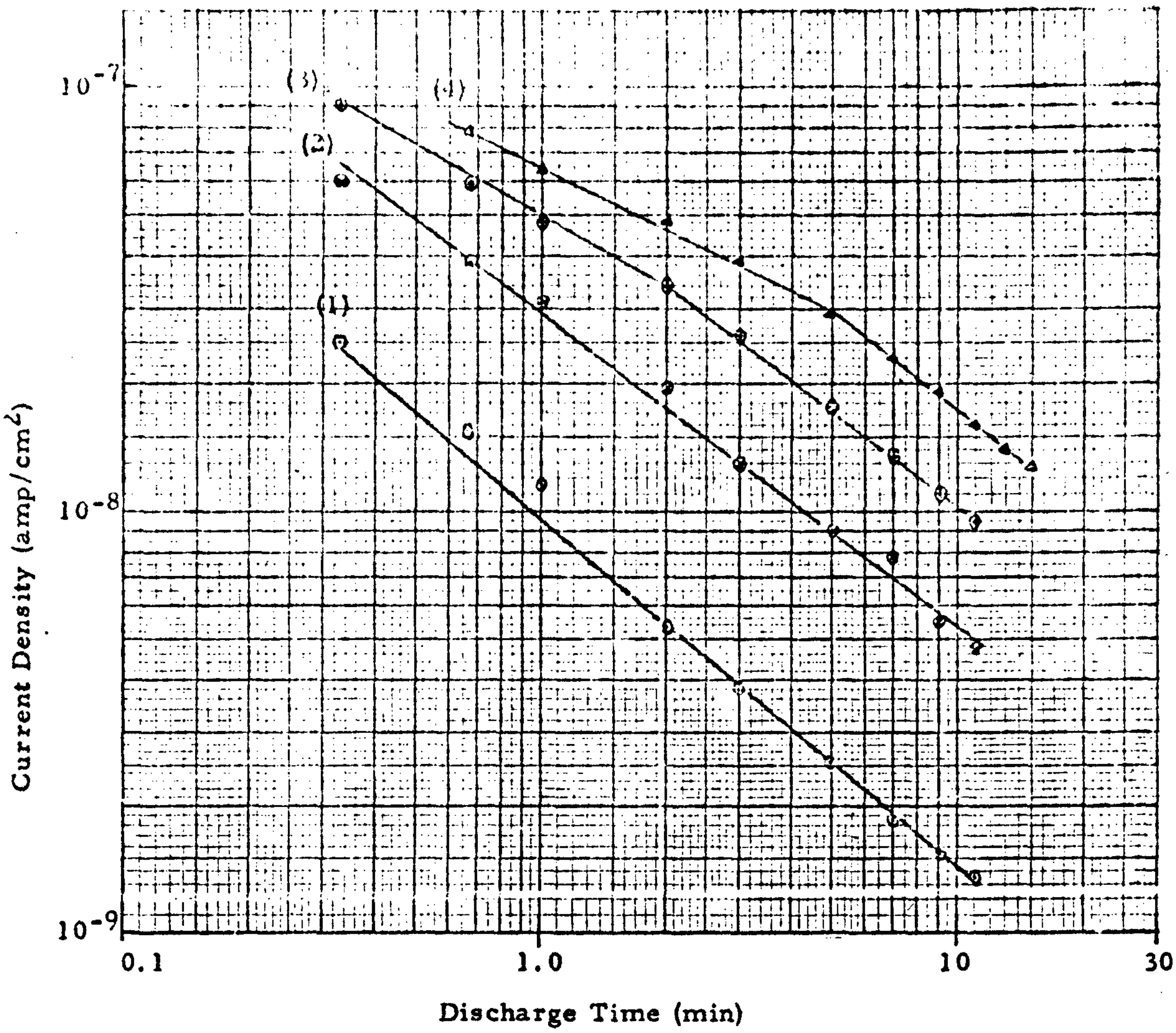


CURRENT AT 85°C VS TIME FOR NEW AND AGED
C67 CASE SIZE I MONOLYTHIC CAPACITORS (~6000 μμF)

Charging Voltage: 45 VDC (18 VDC/Mil)

The capacitors were aged to the indicated resistance at 190 VDC, 150°C

Figure 21

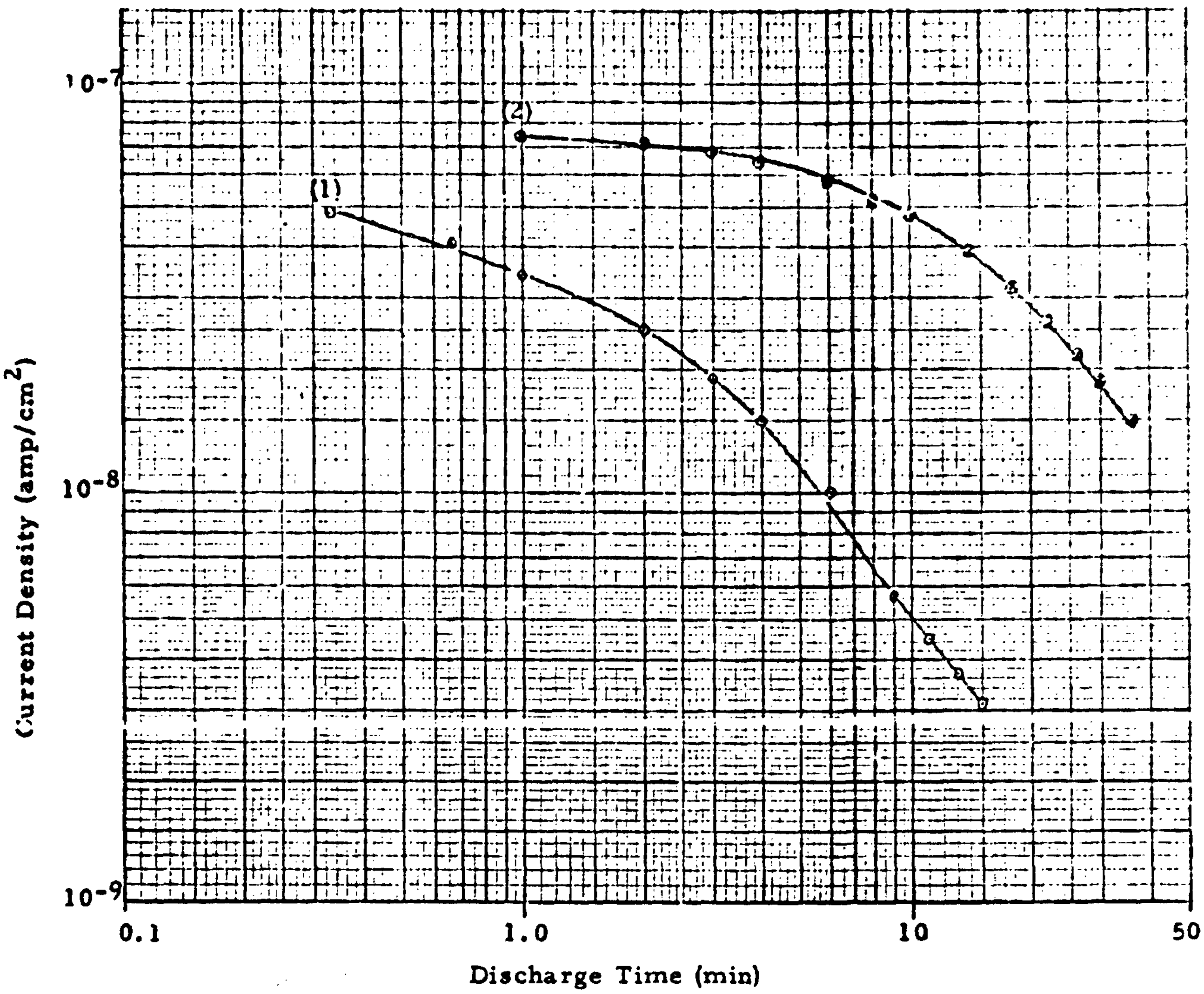


Sequence of Operations

(1) Crystal charged at 6 V for 0.67 min, then discharged
(2) Crystal charged at 6 V for 3 min, then discharged
(3) Crystal charged at 6 V for 6 min, then discharged
(4) Crystal charged at 6 V for 15 min, then discharged

DISCHARGE CURRENT AT 150°C
FOR A $BaTiO_3$ SINGLE CRYSTAL
(Silver-palladium alloy electrodes: area - 0.10 cm^2, thickness - 0.027 cm)

Figure 22

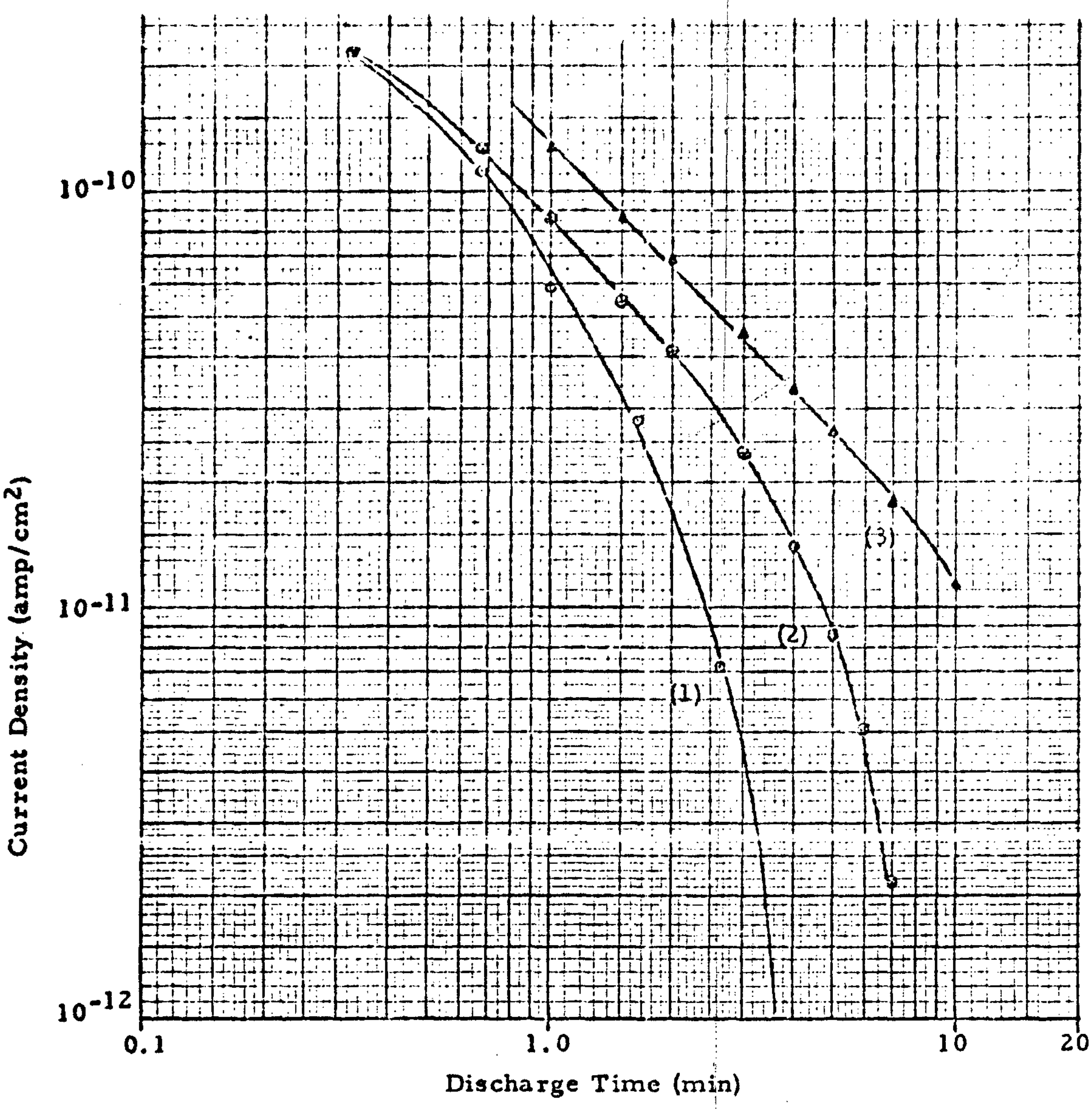


Sequence of Operations

(1) Crystal charged at 6 V for 1.3 min, then discharged
(2) Crystal charged at 6 V for 15 min, then discharged

DISCHARGE CURRENT AT 150°C
FOR A $BaTiO_3$ SINGLE CRYSTAL
(Silver electrodes: area - 0.12 cm^2, thickness - 0.035 cm)

Figure 23



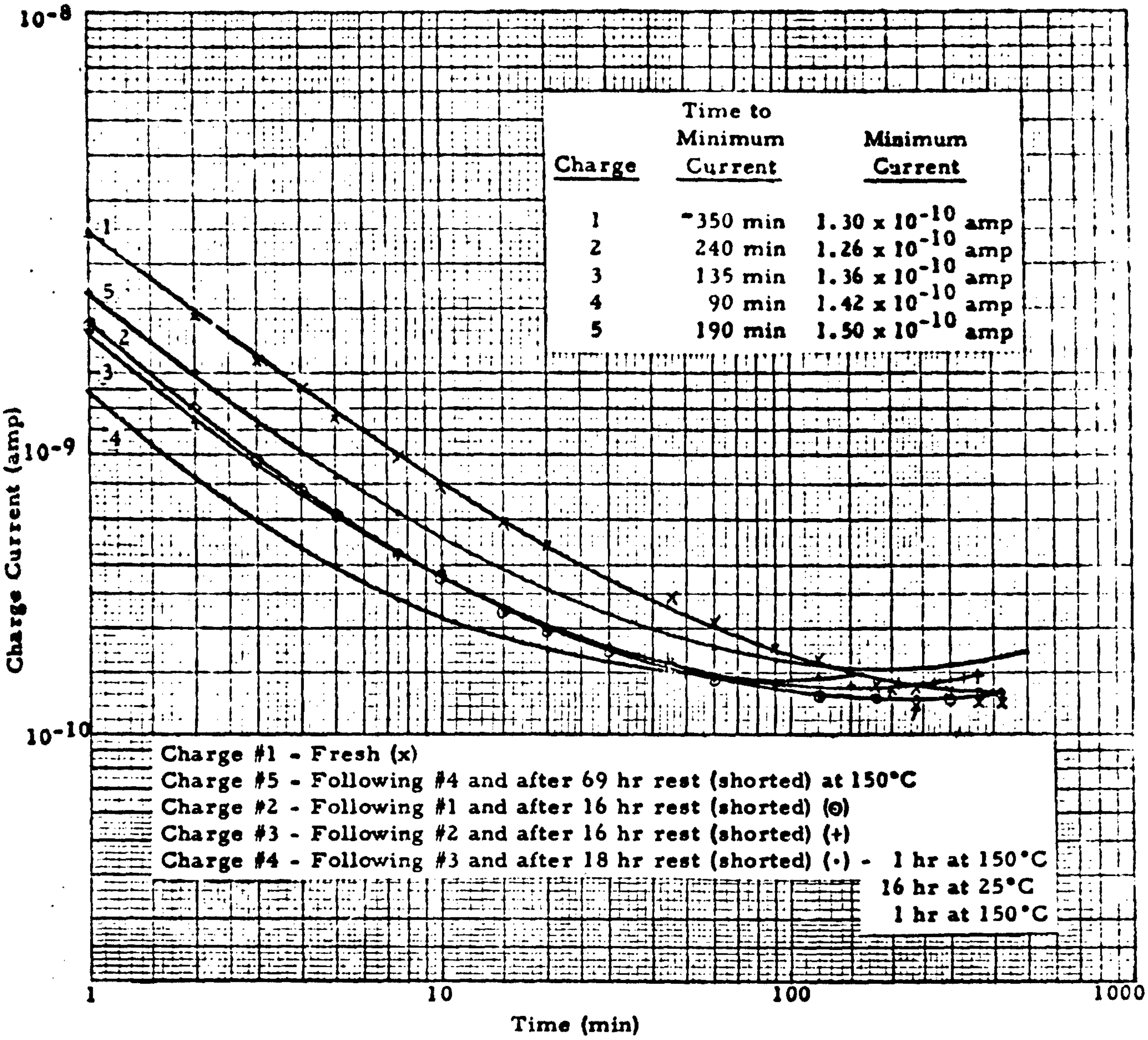
<u>Sequence of Operations</u>

(1) Capacitor charged at 6 V for 1 min, then discharged
(2) Capacitor charged at 6 V for 5 min, then discharged
(3) Capacitor charged at 6 V for 30 min, then discharged

DISCHARGE CURRENT AT 150°C
FOR A C67 CASE SIZE I MONOLYTHIC CAPACITOR

(Dielectric area: 0.51 cm^2; dielectric thickness: 0.0064 cm)

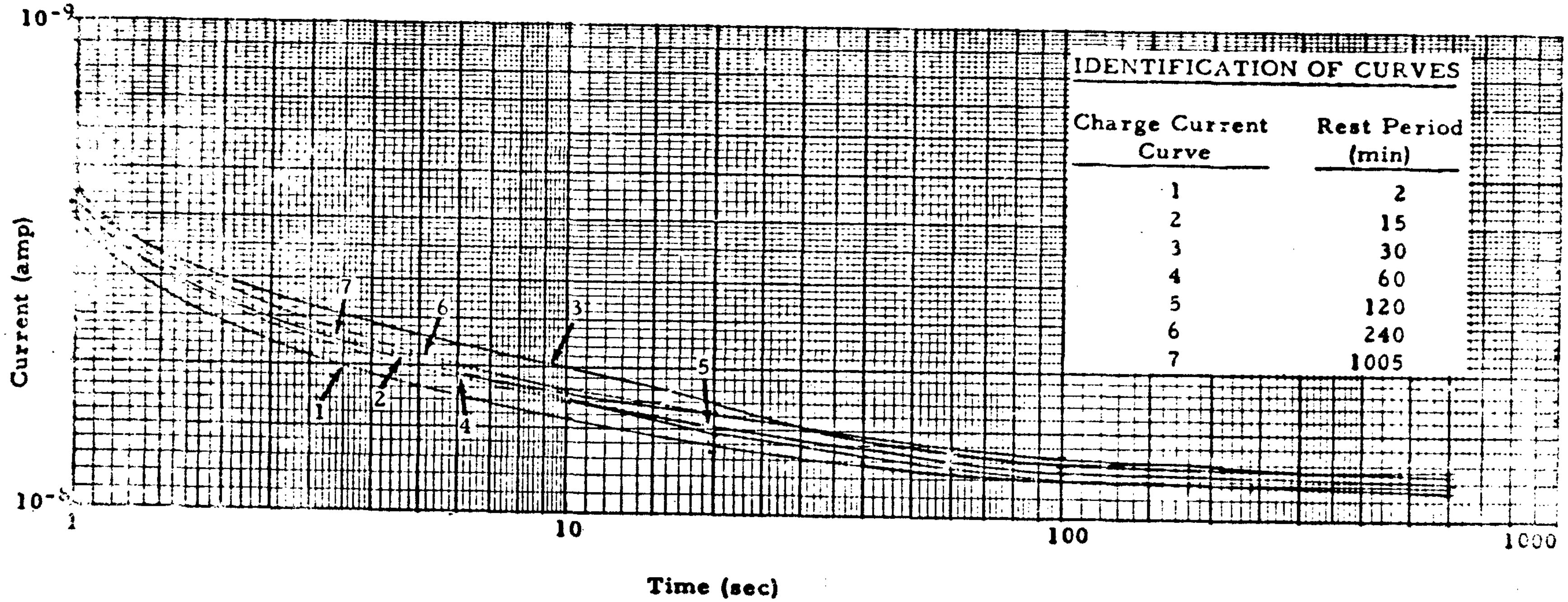
Figure 24



CHARGE CURRENT VS TIME
FOR A 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITOR (Lot 449)

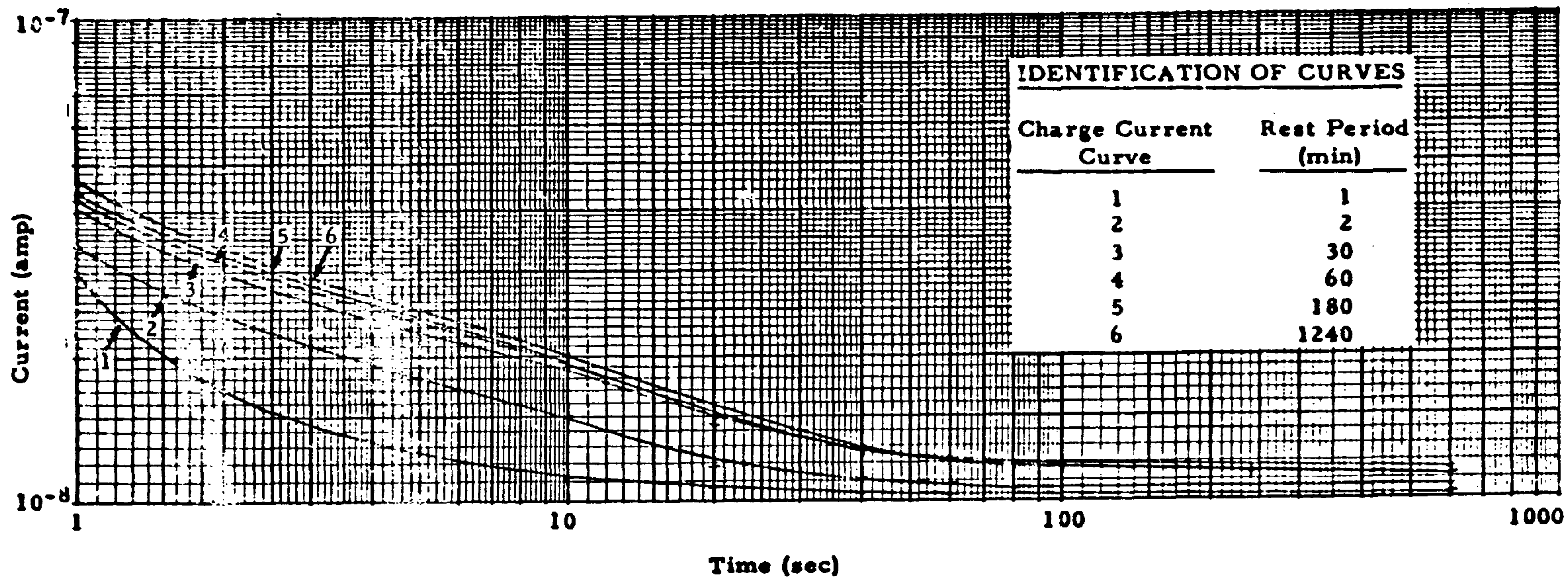
Charge Condition: 230 VDC, 150°C

Figure 25



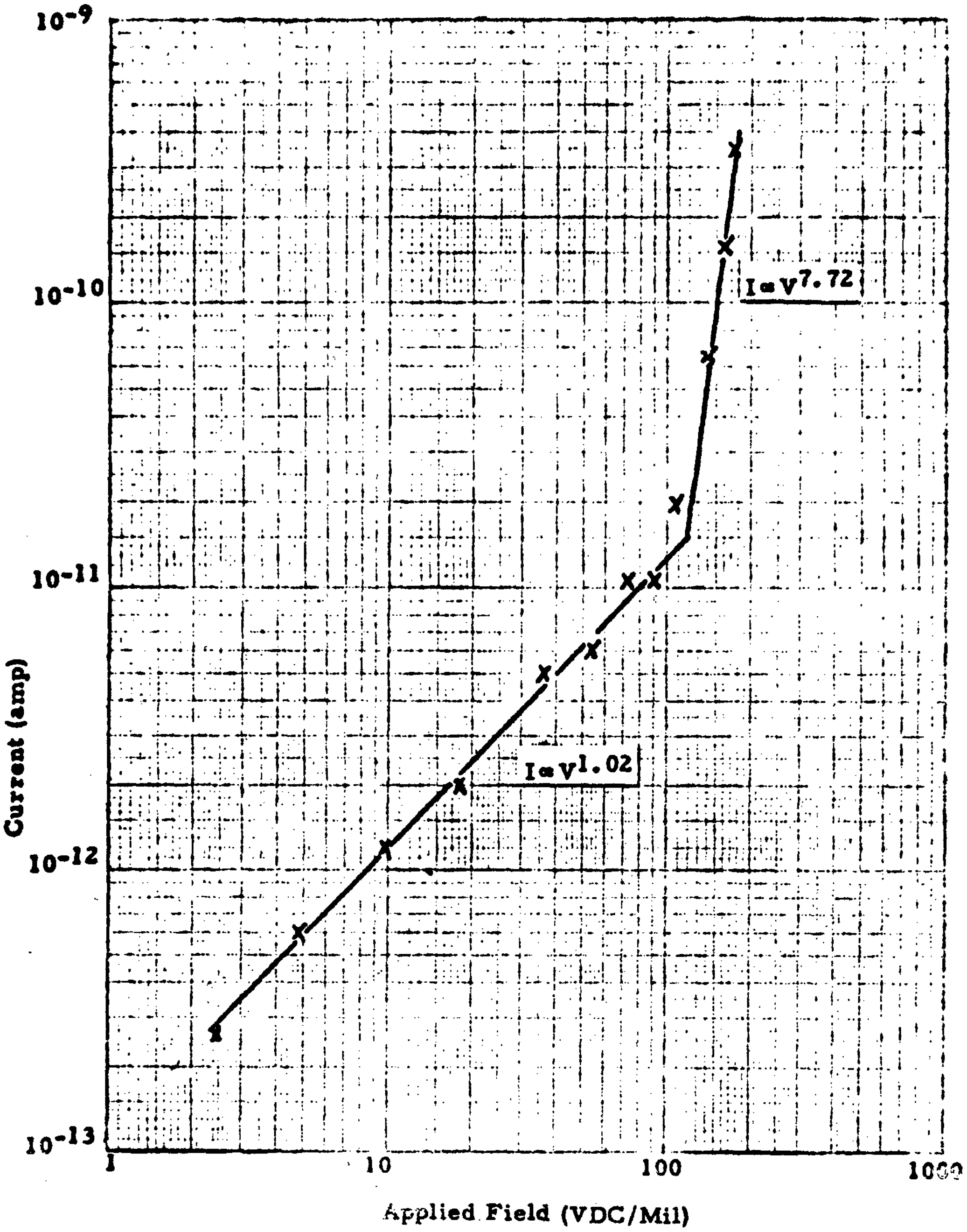
CHARGE CURRENTS AT 95 VDC, 150°C
ON C67 CASE SIZE I MONOLYTHIC CAPACITOR (~8000 μμF)
FOLLOWING VARIOUS REST PERIODS IN CLOSED CIRCUIT

Figure 26



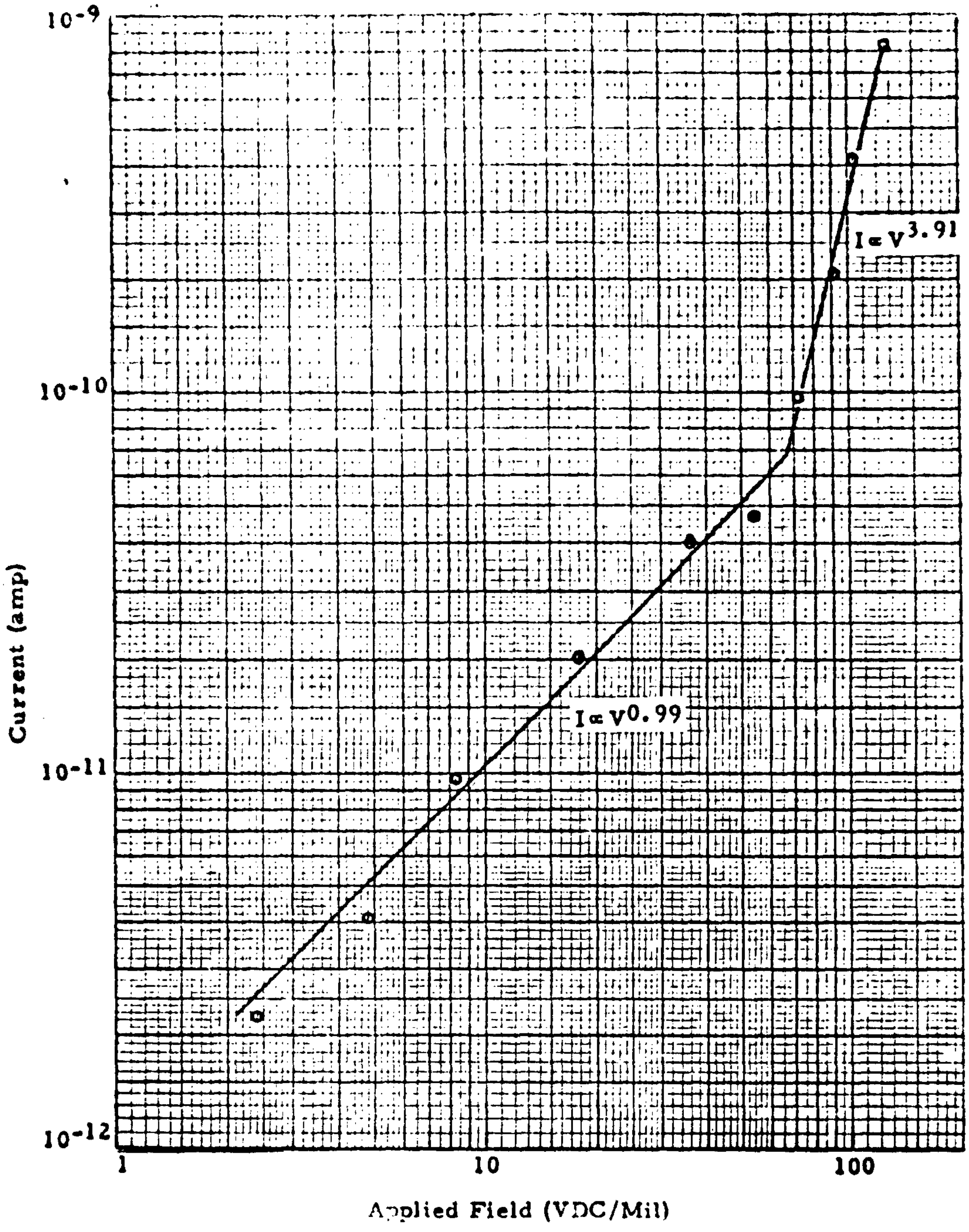
CHARGE CURRENTS AT 95 VDC, 150°C
ON C67 CASE SIZE I MONOLYTHIC CAPACITOR (~8000 μμF)
FOLLOWING VARIOUS REST PERIODS IN OPEN CIRCUIT

Figure 27



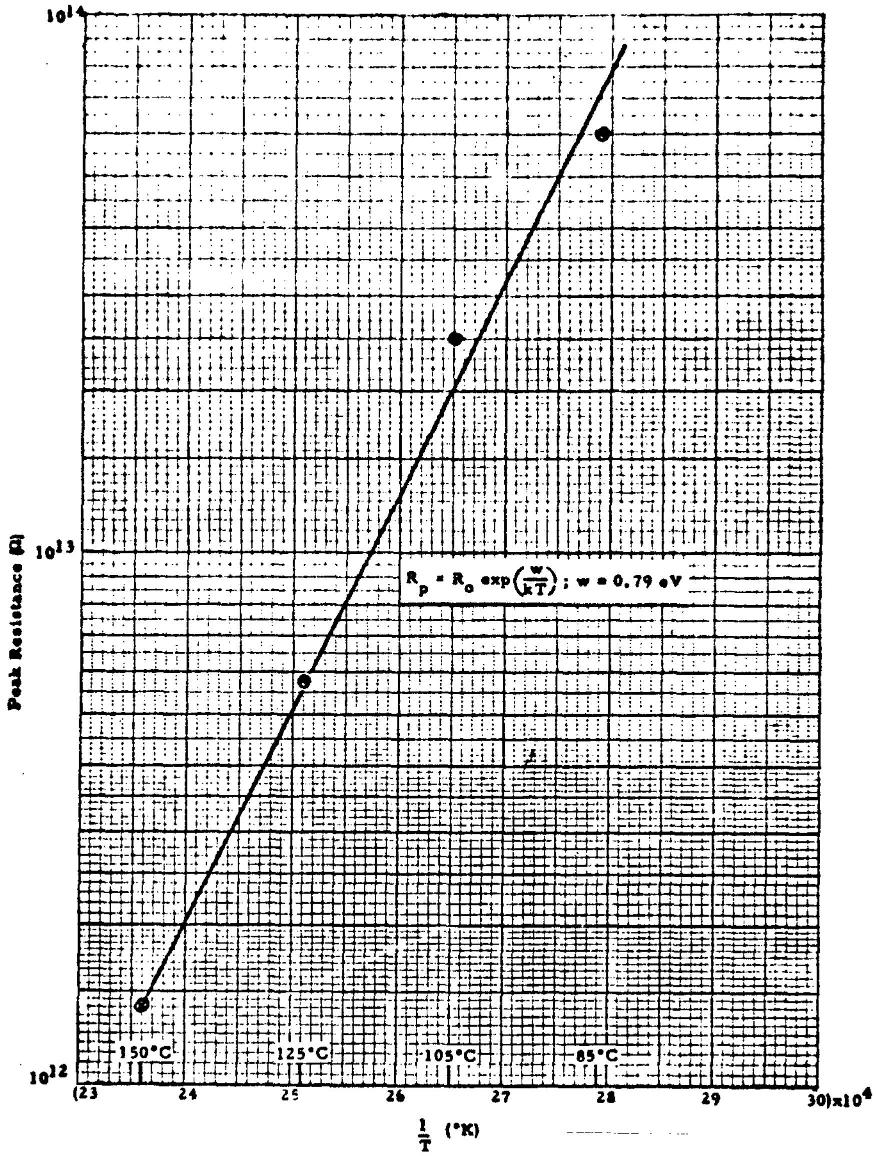
STEADY-STATE CURRENT
VS APPLIED FIELD AT 85°C
FOR
NEW C67 CASE SIZE I MONOLYTHIC CAPACITOR (6000 μμF)
Dielectric Thickness: 0.0025 in.

Figure 28



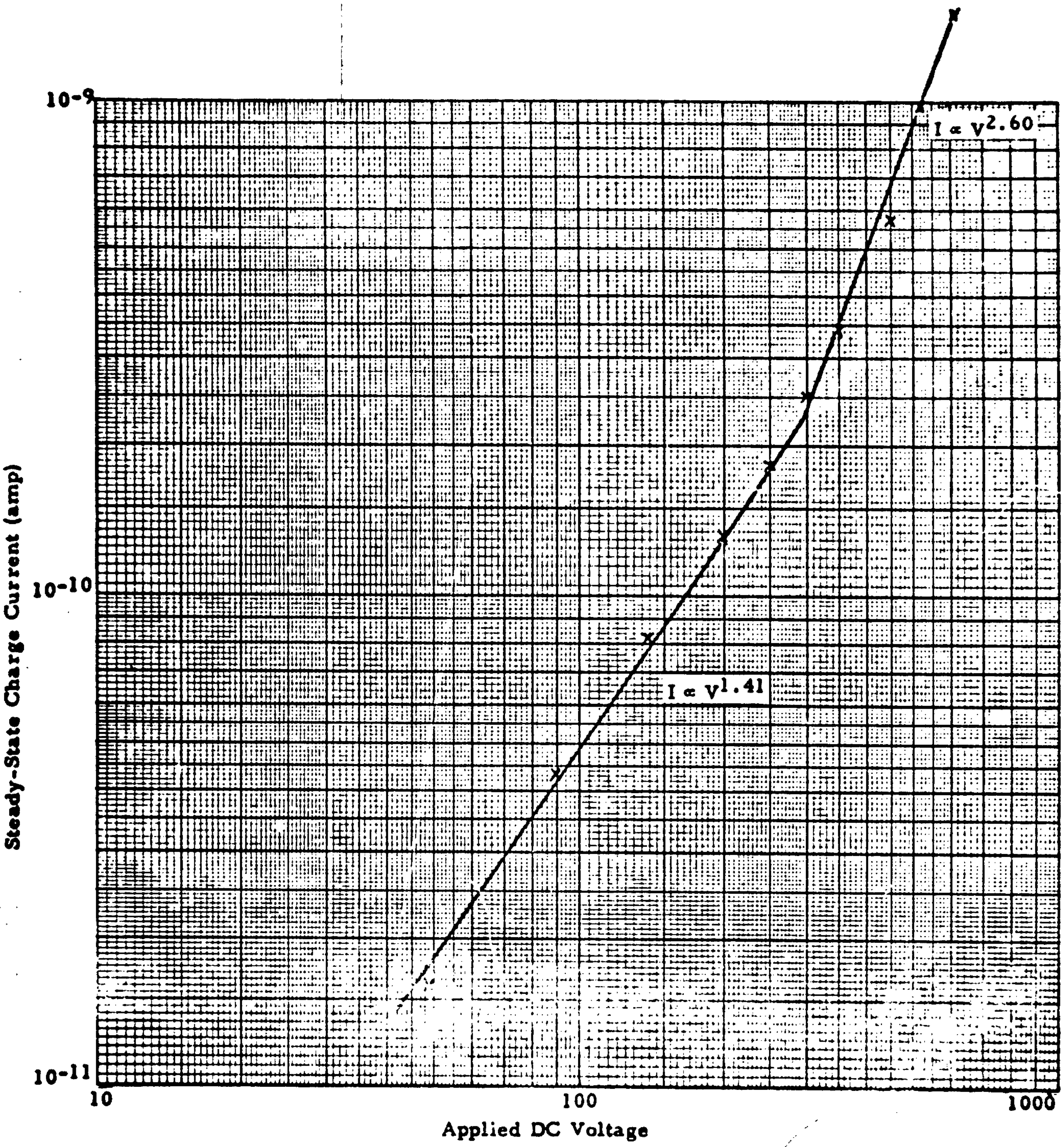
STEADY-STATE CURRENT
VS APPLIED FIELD AT 150°C
FOR
NEW G67 CASE SIZE I MONOLYTHIC CAPACITOR (6000 μμF)
Dielectric Thickness: 0.0025 in.

Figure 29



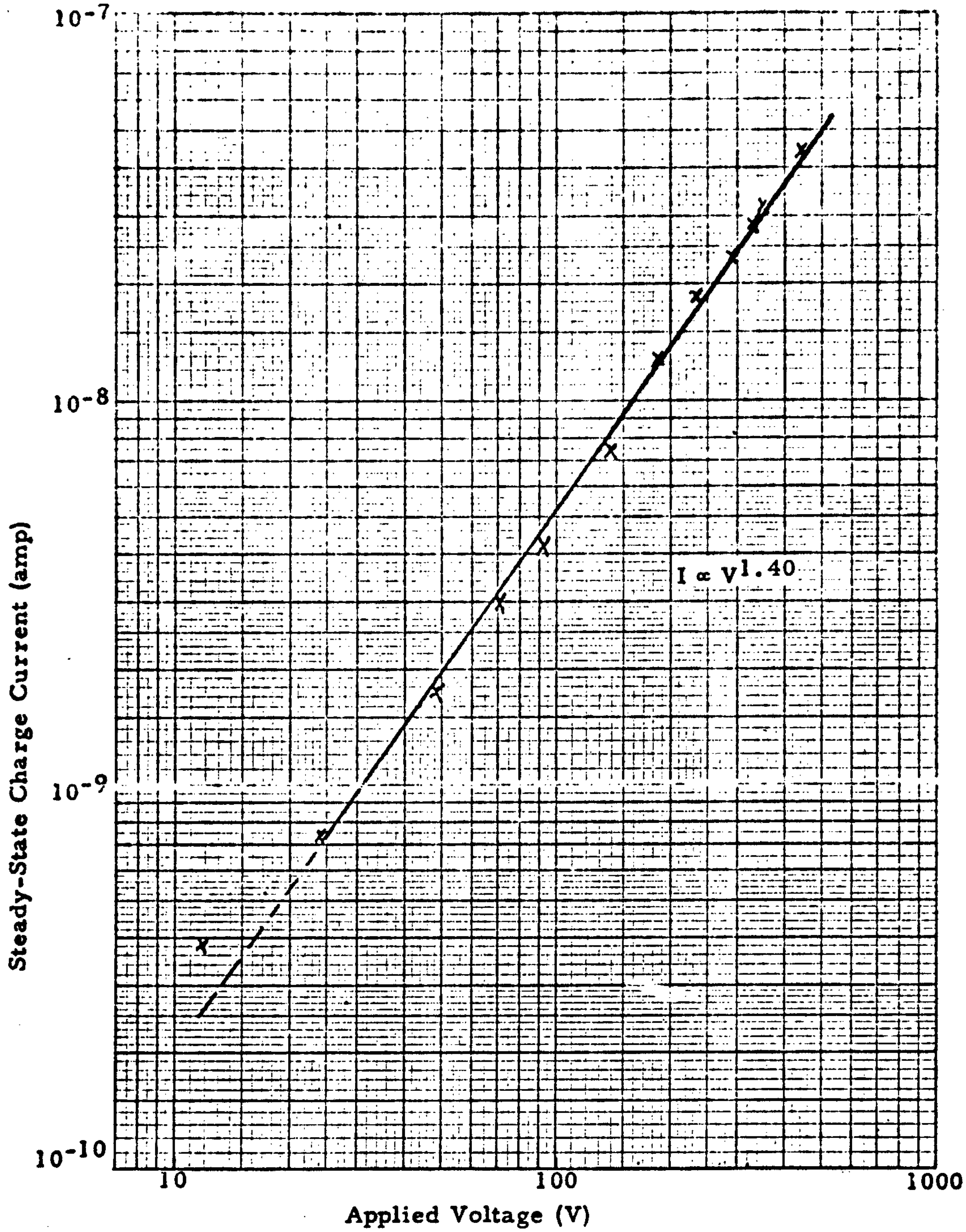
PEAK RESISTANCE VS
INVERSE ABSOLUTE TEMPERATURE AT 220 VDC
FOR 0.01 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS (Lot 449)

Figure 30



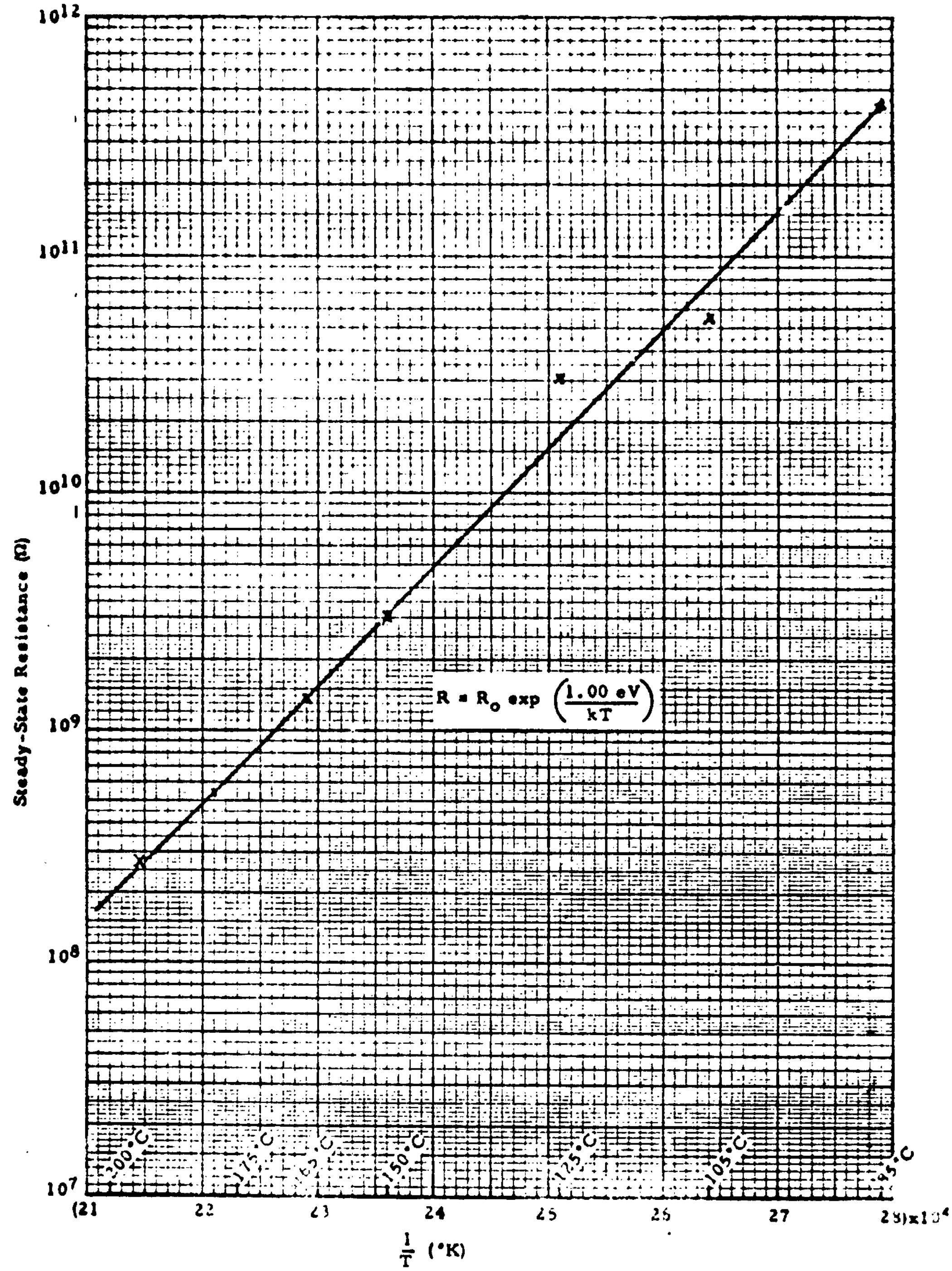
STEADY-STATE CHARGE CURRENT VS VOLTAGE AT 85°C
FOR A NEW, IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITOR
Dielectric Thickness: 0.0025 in.

Figure 31



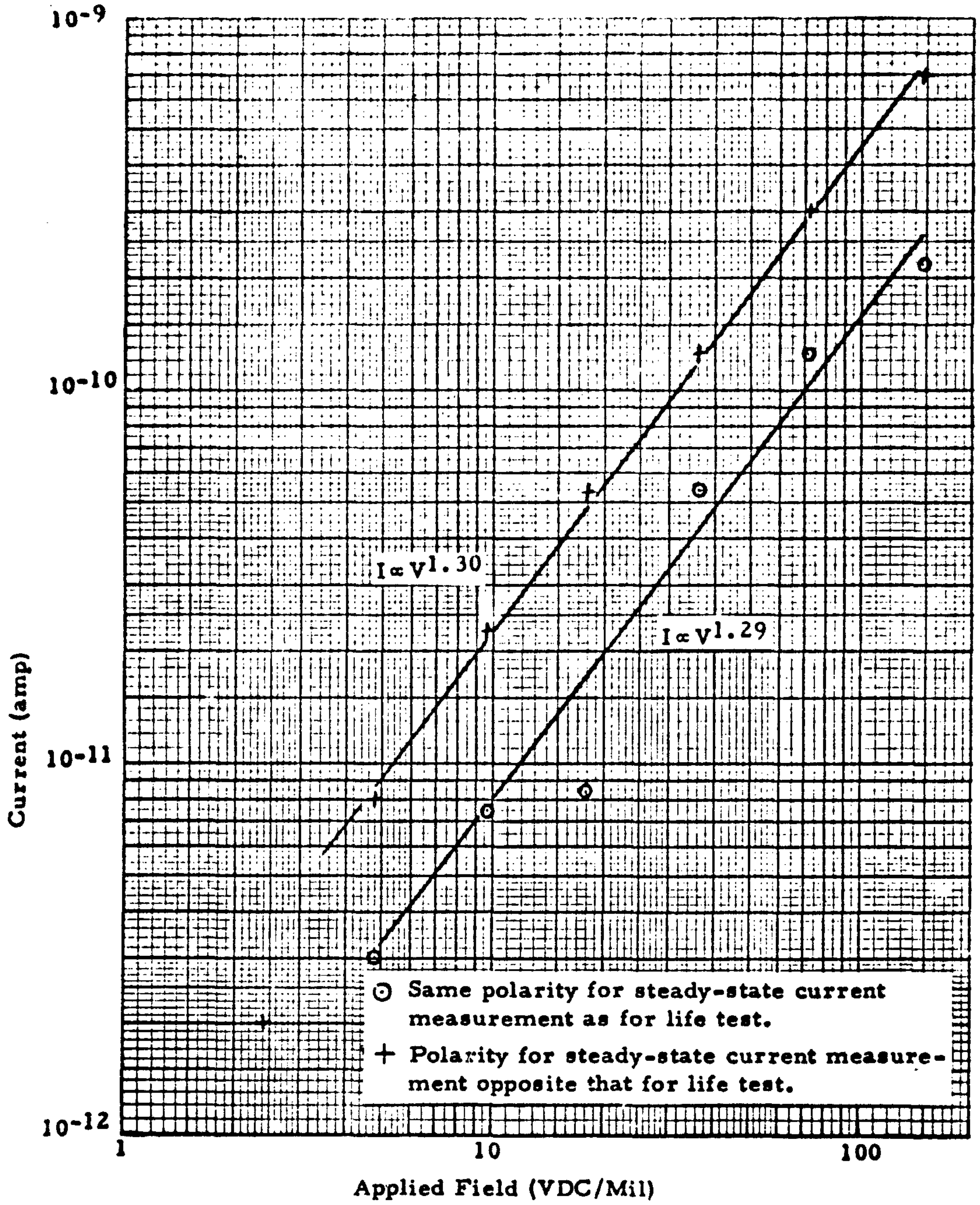
STEADY-STATE CHARGE CURRENT
VS APPLIED VOLTAGE AT 150°C
FOR A 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITOR (Lot 830)
(Dielectric thickness in this capacitor is 0.0025 in.)

Figure 32



STEADY-STATE RESISTANCE
VS INVERSE ABSOLUTE TEMPERATURE AT 200 VDC
FOR A NEW, IMPROVED 0.01 µF C67 CASE SIZE 1 MONOLYTHIC CAPACITOR

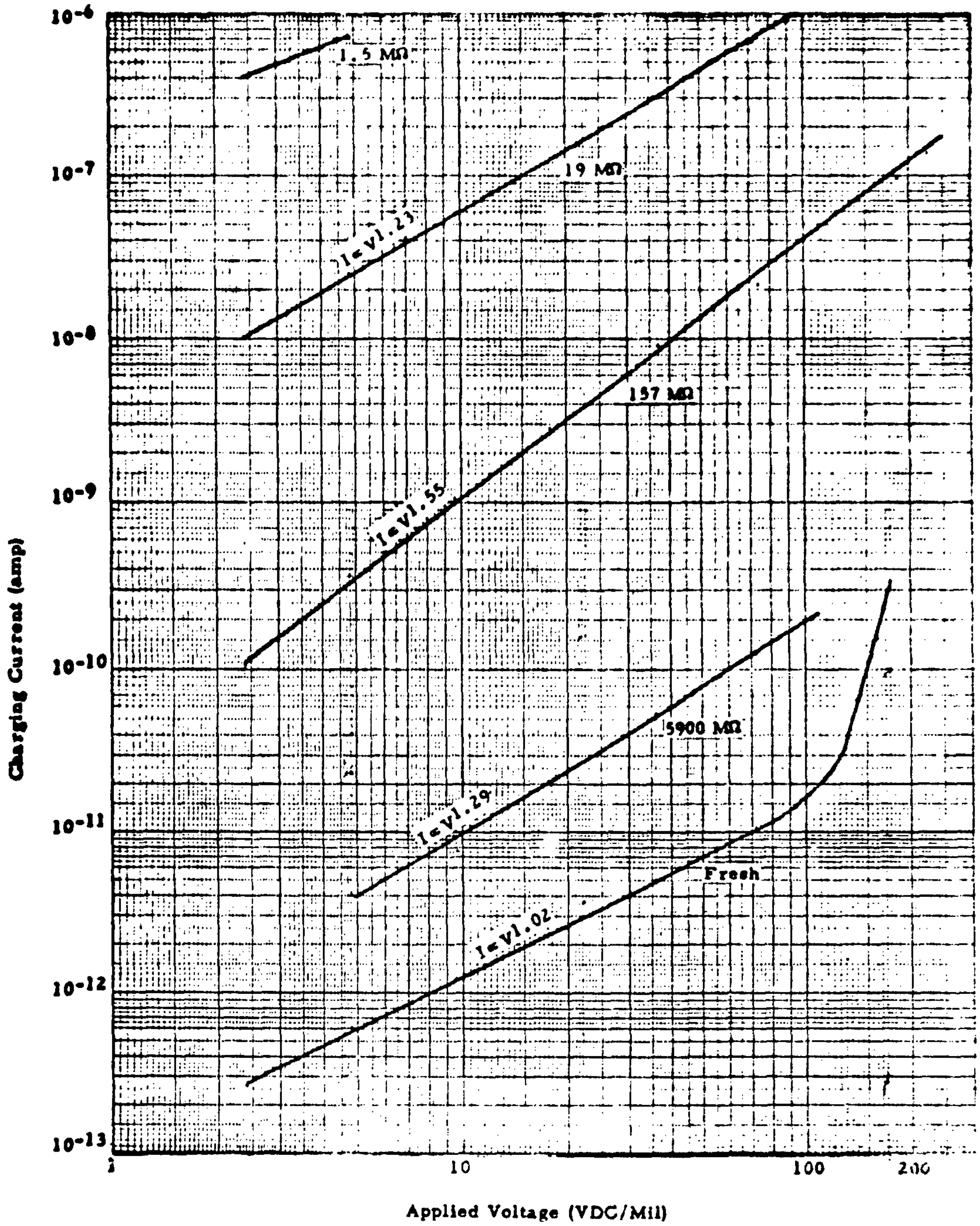
Figure 33



STEADY-STATE CURRENT
VS APPLIED FIELD AT 85°C
FOR
A C67 CASE SIZE I MONOLYTHIC CAPACITOR (6000 μμF)

(Resistance of this capacitor was degraded to 5900 MΩ by life testing at 190 V, 150°C.)

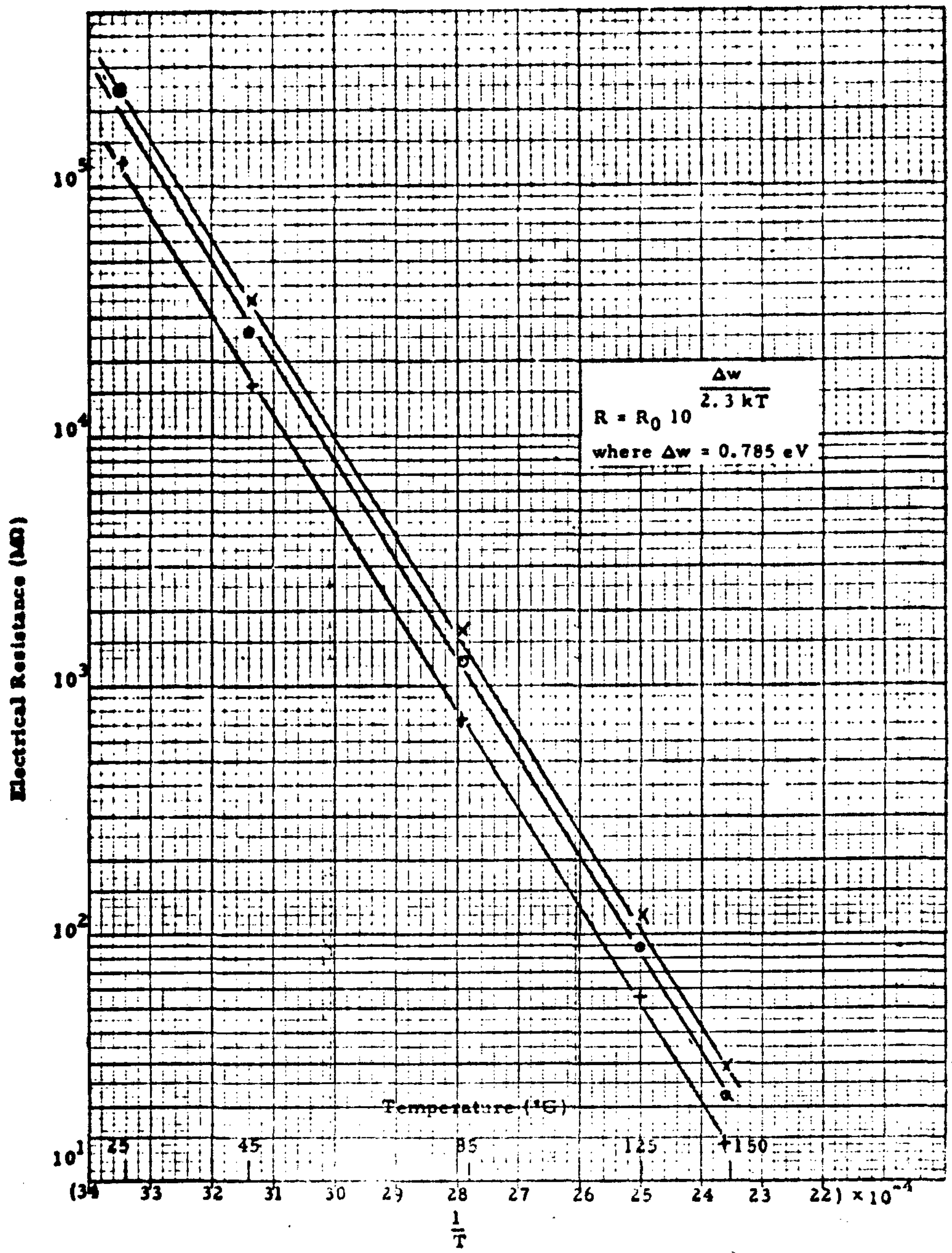
Figure 34.



STEADY-STATE CURRENT AT 85°C
VS APPLIED FIELD FOR FRESH AND AGED
C67 CASE SIZE I MONOLYTHIC CAPACITORS (-600...

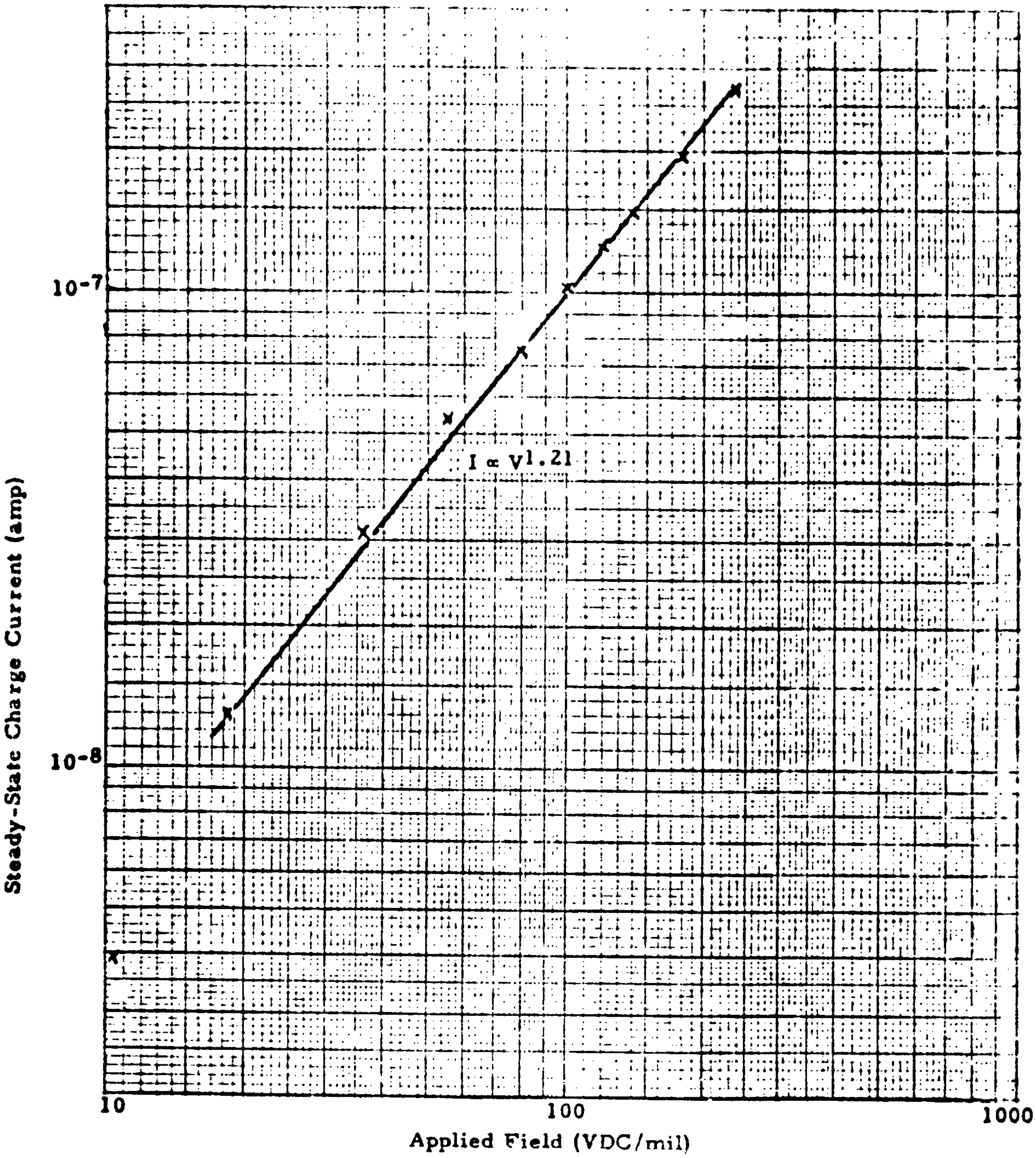
(The capacitors were aged to the indicated resistance ... 90 VDC, 150°C)
(Dielectric Thickness: 0.0025 in.)

Figure 35



RESISTANCE VS TEMPERATURE
FOR C67 CASE SIZE I MONOLITHIC CAPACITORS
(Units first subjected to 75 VDC/mil at 150°C for 500 hr;
temperature then lowered in steps while voltage maintained.)

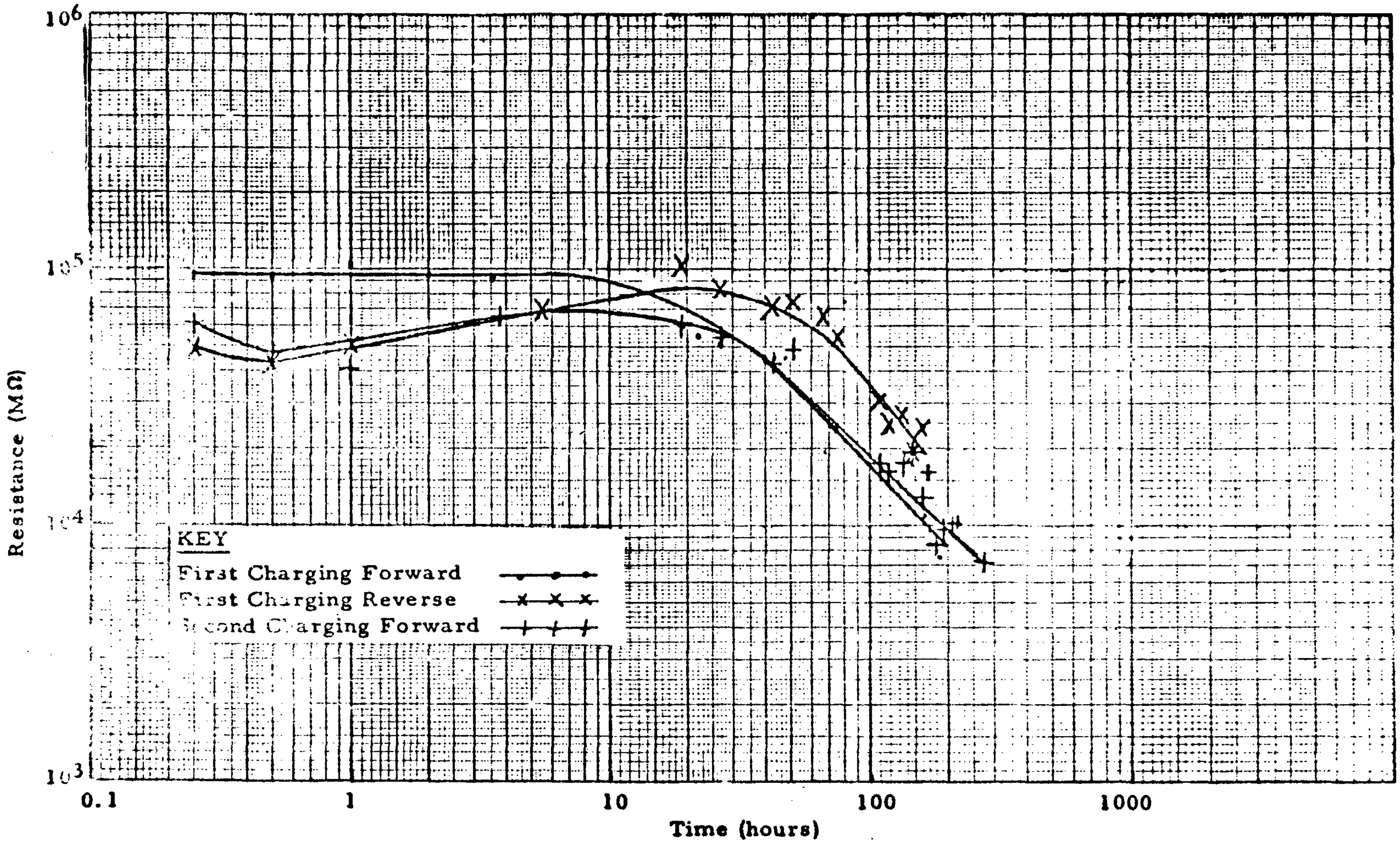
Figure 36



STEADY-STATE CHARGE CURRENT VS APPLIED FIELD AT 150°C FOR AN IMPROVED 0.01 µF C67 CASE SIZE I MONOLYTHIC CAPACITOR (Lot [illegible]) WHICH WAS AGED

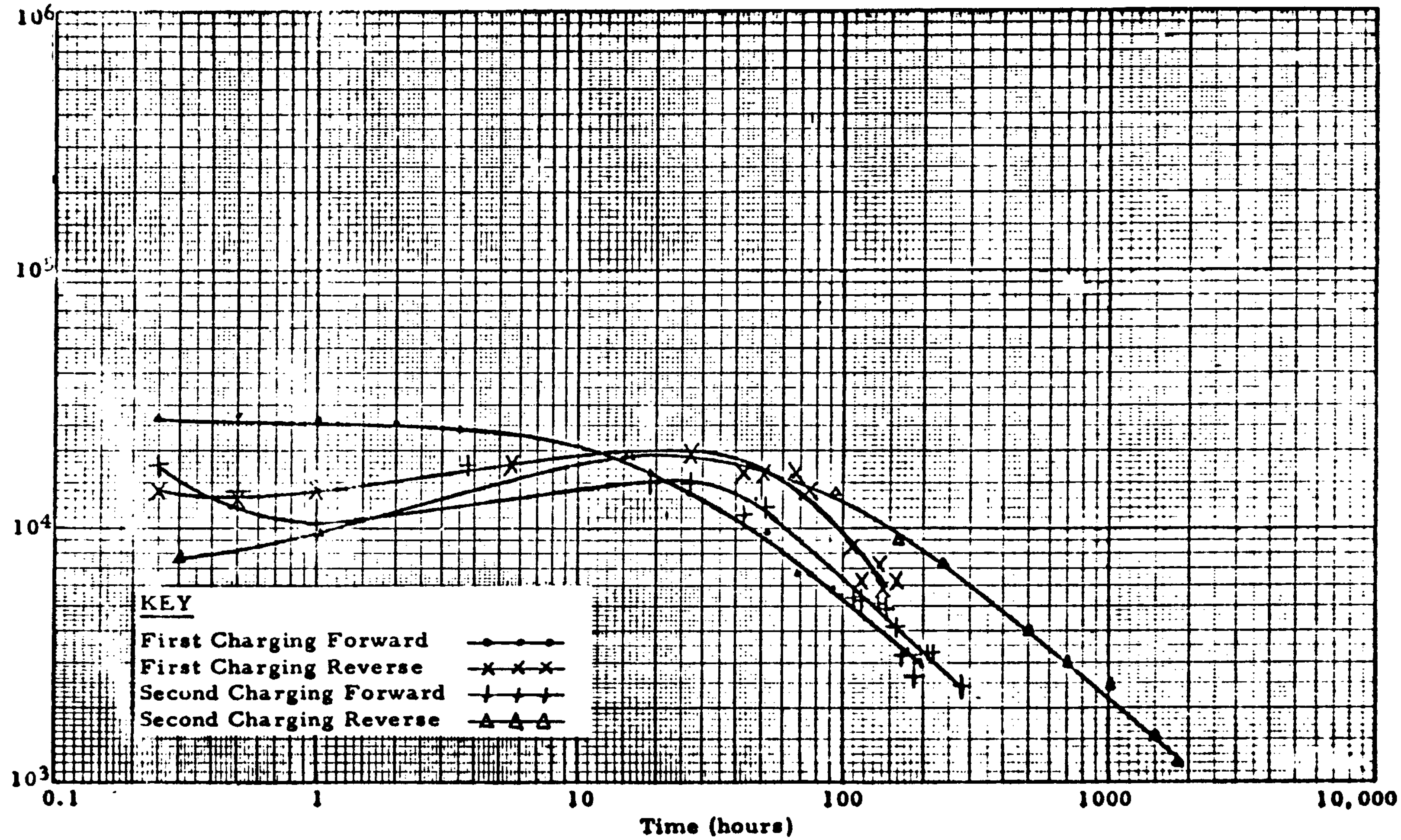
Notes: **(1)** Charge current applied in same polarity as **used during aging**
(2) Capacitor aged at 150°C for 820 hr with 240 **VDC/mil.**
During aging, resistance decreased from **10,400 MΩ to 2400 MΩ**

Figure 37



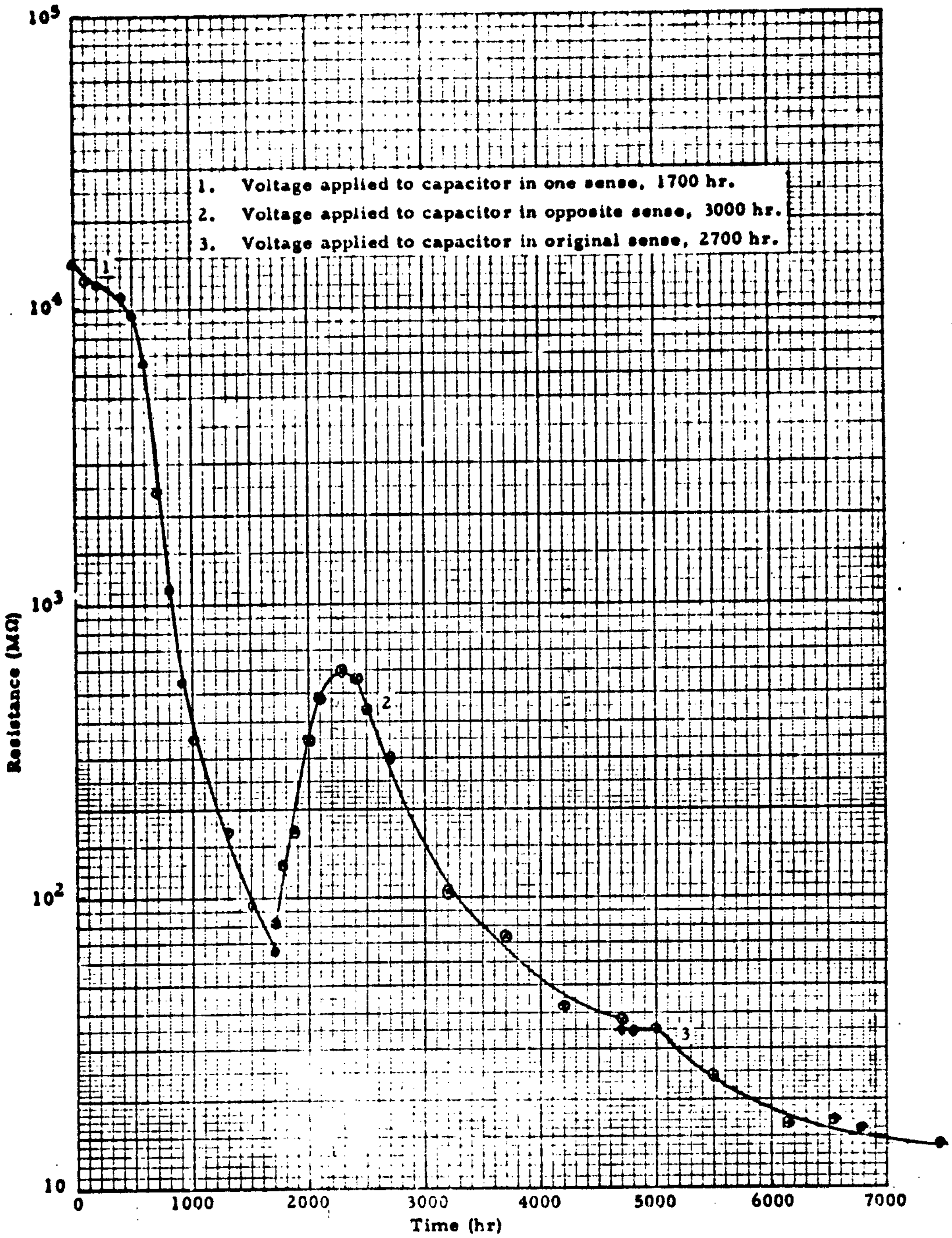
RESISTANCE VS TIME AT 195 VDC, 150°C
FOR A 0.01 µF CASE SIZE I C67 MONOLYTHIC CAPACITOR (Lot 659205, No. 30841)

Figure 38



RESISTANCE VS TIME AT 195 VDC, 150°C
FOR A 0.01 μF CASE SIZE I C67 MONOLYTHIC CAPACITOR (Lot 6S9205, No. 30844)

Figure 39

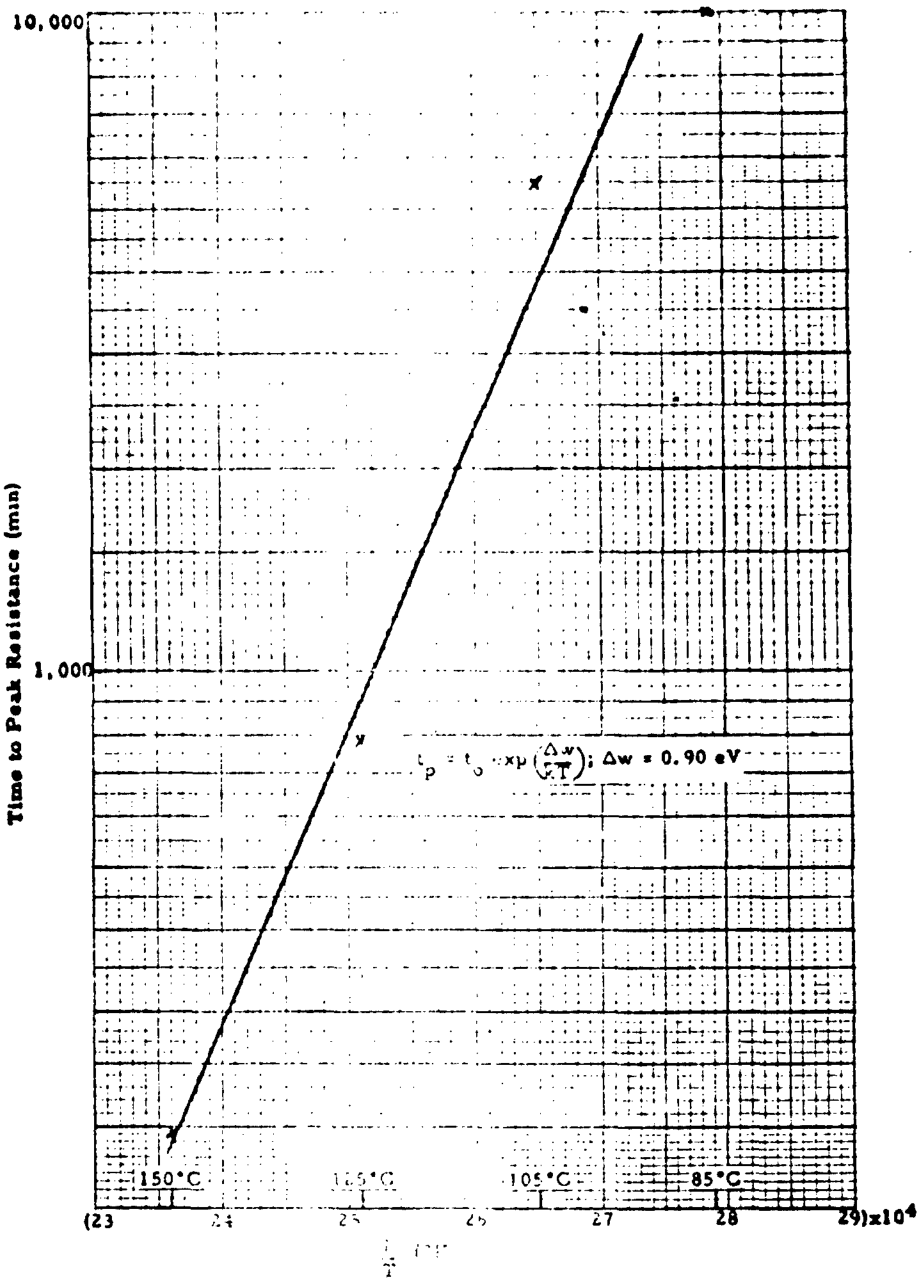


RESISTANCE VS TIME

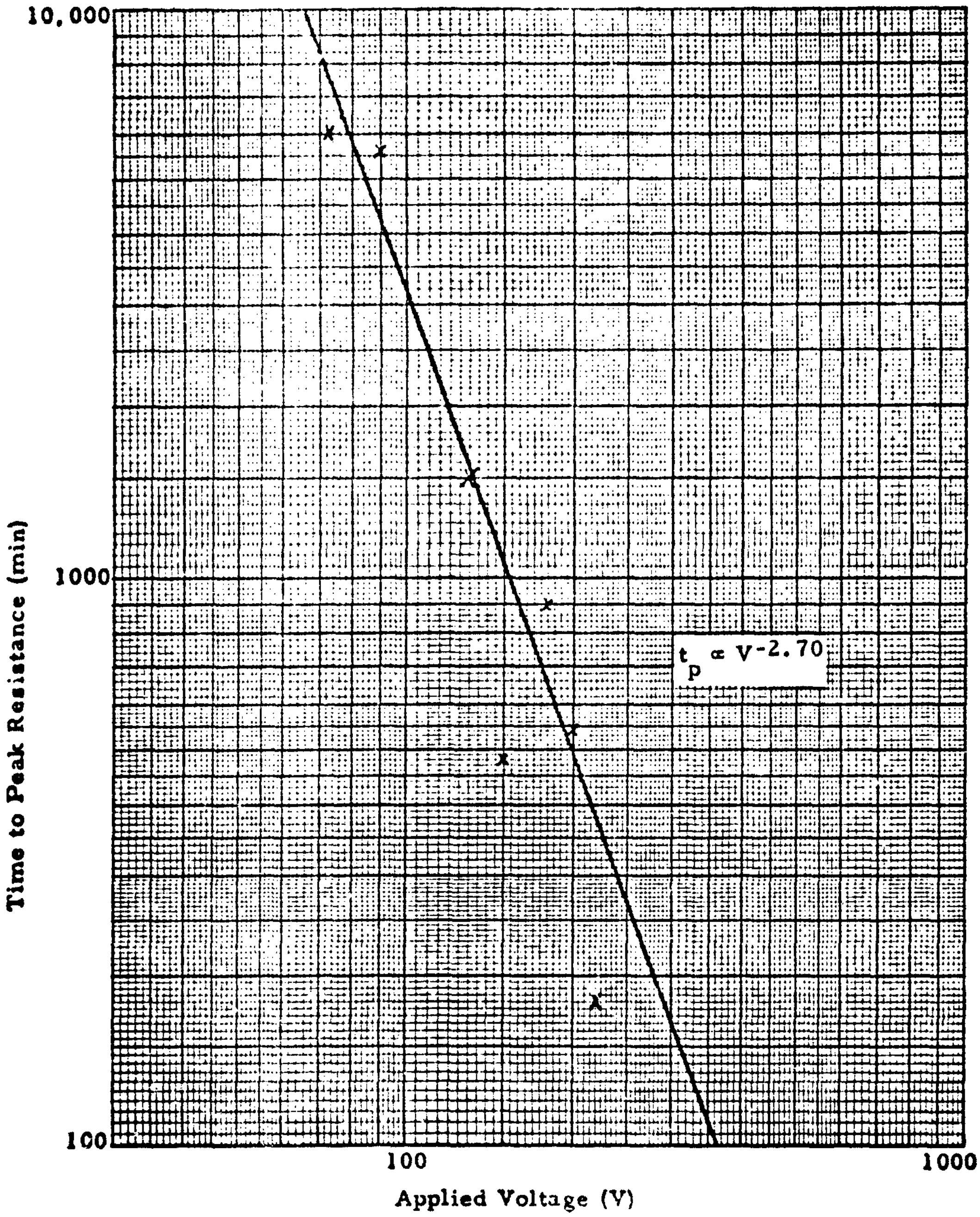
FOR IMPROVED 0.01 µF C6[illegible] CASE [illegible] MONOLYTHIC CAPACITOR NO. 0169

[illegible]: 150°C, 220 VDC

Figure 40



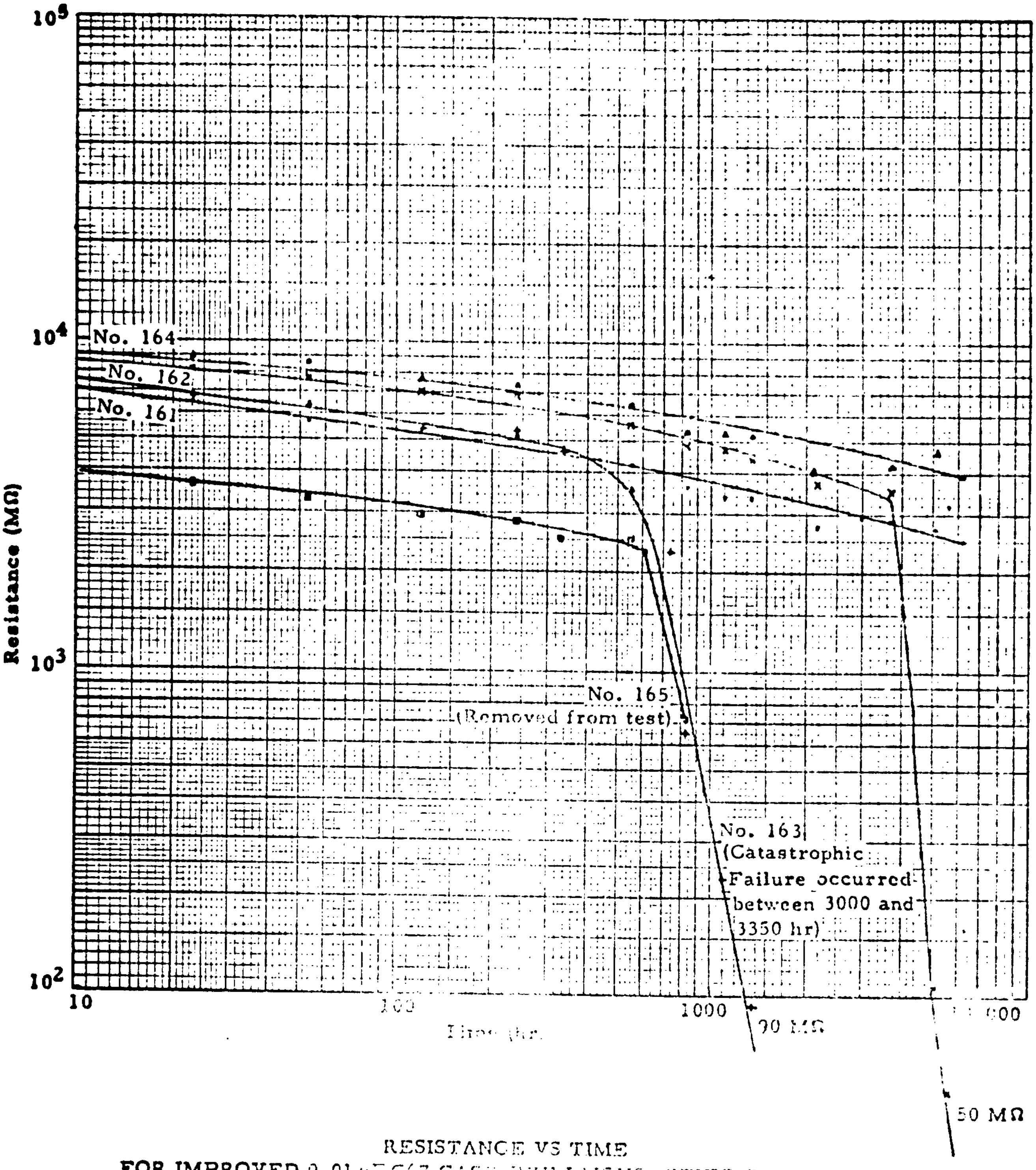
TIME TO PEAK RESISTANCE VS
INVERSE ABSOLUTE TEMPERATURE AT 220 VDC
FOR 0.01 μF C67 CERAMIC MONOLYTHIC CAPACITORS (Lot 449)



TIME TO PEAK RESISTANCE
VS VOLTAGE AT 150°C
FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (Lot 449)

(Dielectric thickness in these capacitors is 0.0025 in.)

Figure 42



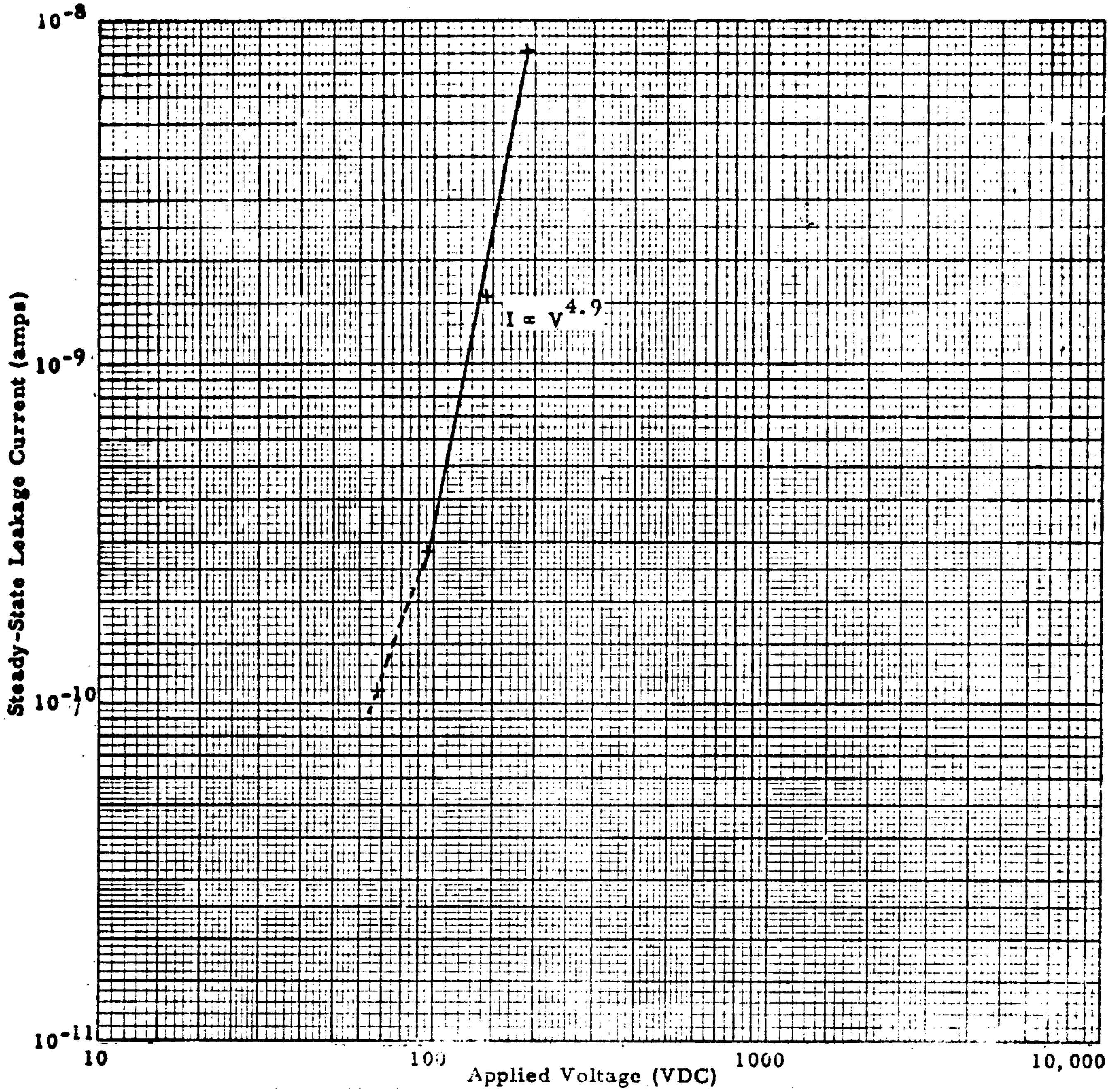
RESISTANCE VS TIME

FOR IMPROVED 0.01 μF C47 CASE SIZE MONOLYTHIC C... ...TORS

D.ele... ... 0.0025 ...

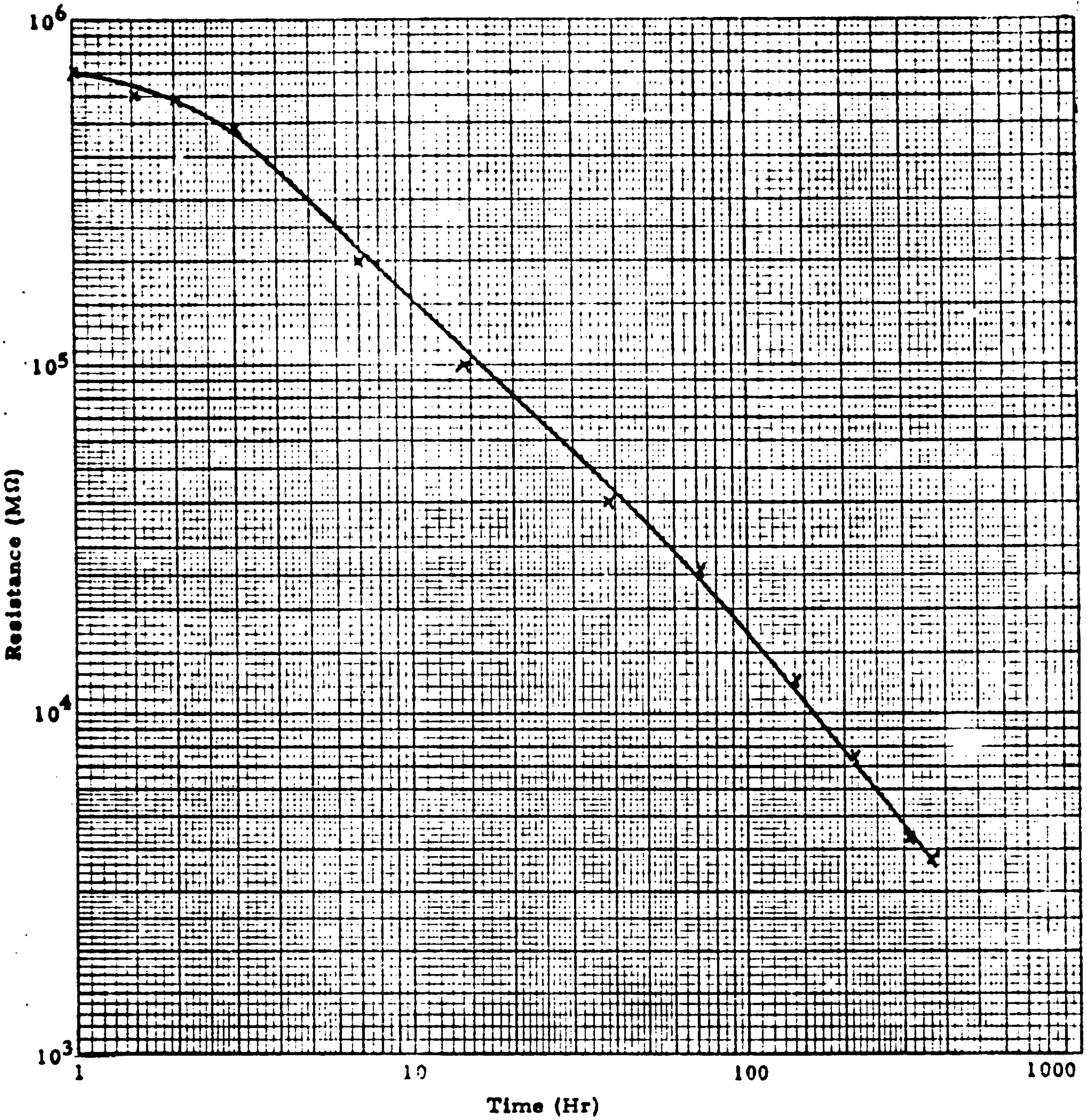
C... ... 15... 600 V...

Figure 4?



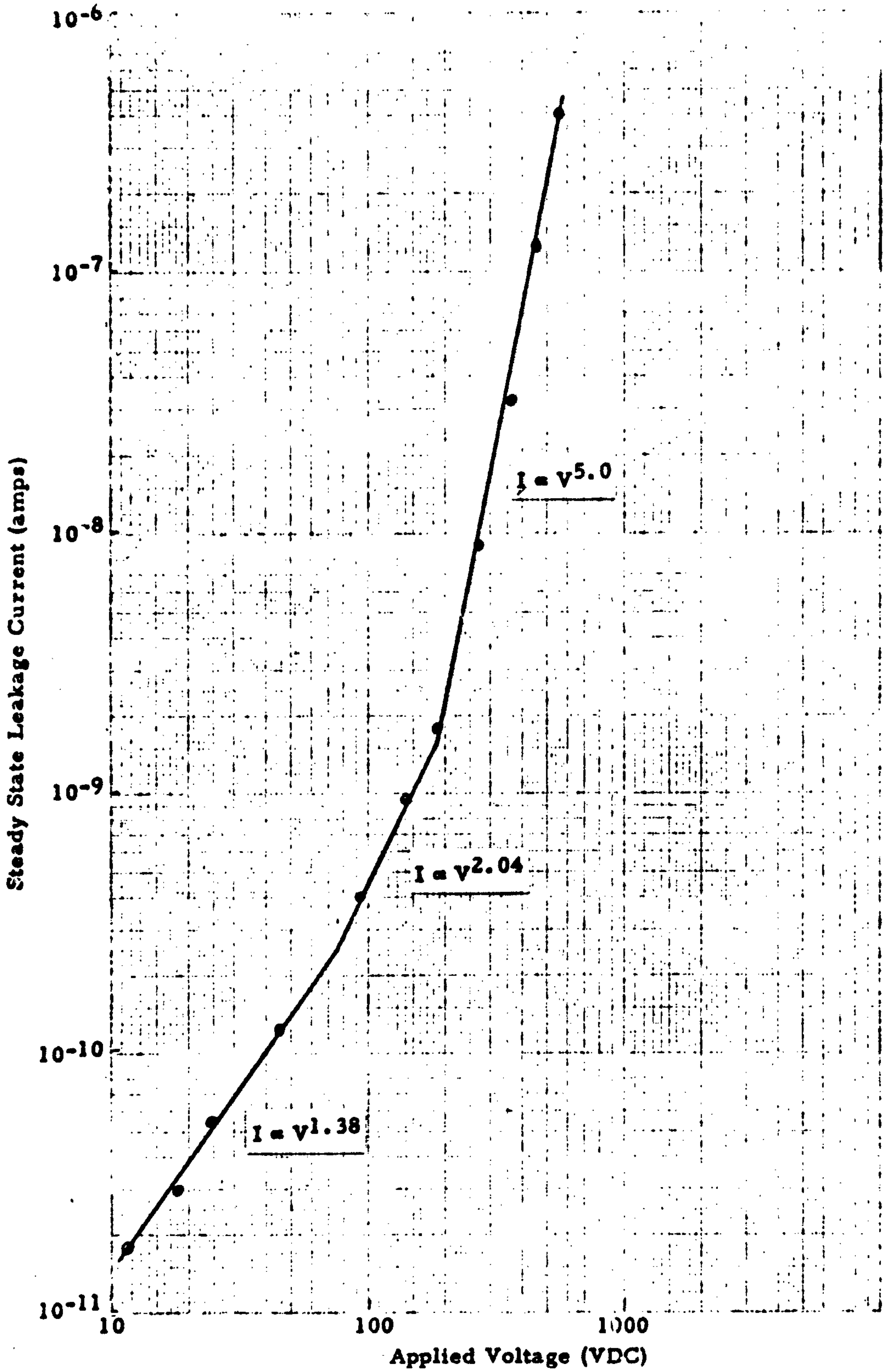
STEADY-STATE LEAKAGE CURRENT VS APPLIED VOLTAGE AT 150°C FOR A LOT D269 CAPACITOR (C67 MONOLYTHIC 0.01 µF Case Size I Capacitor)

Figure 44



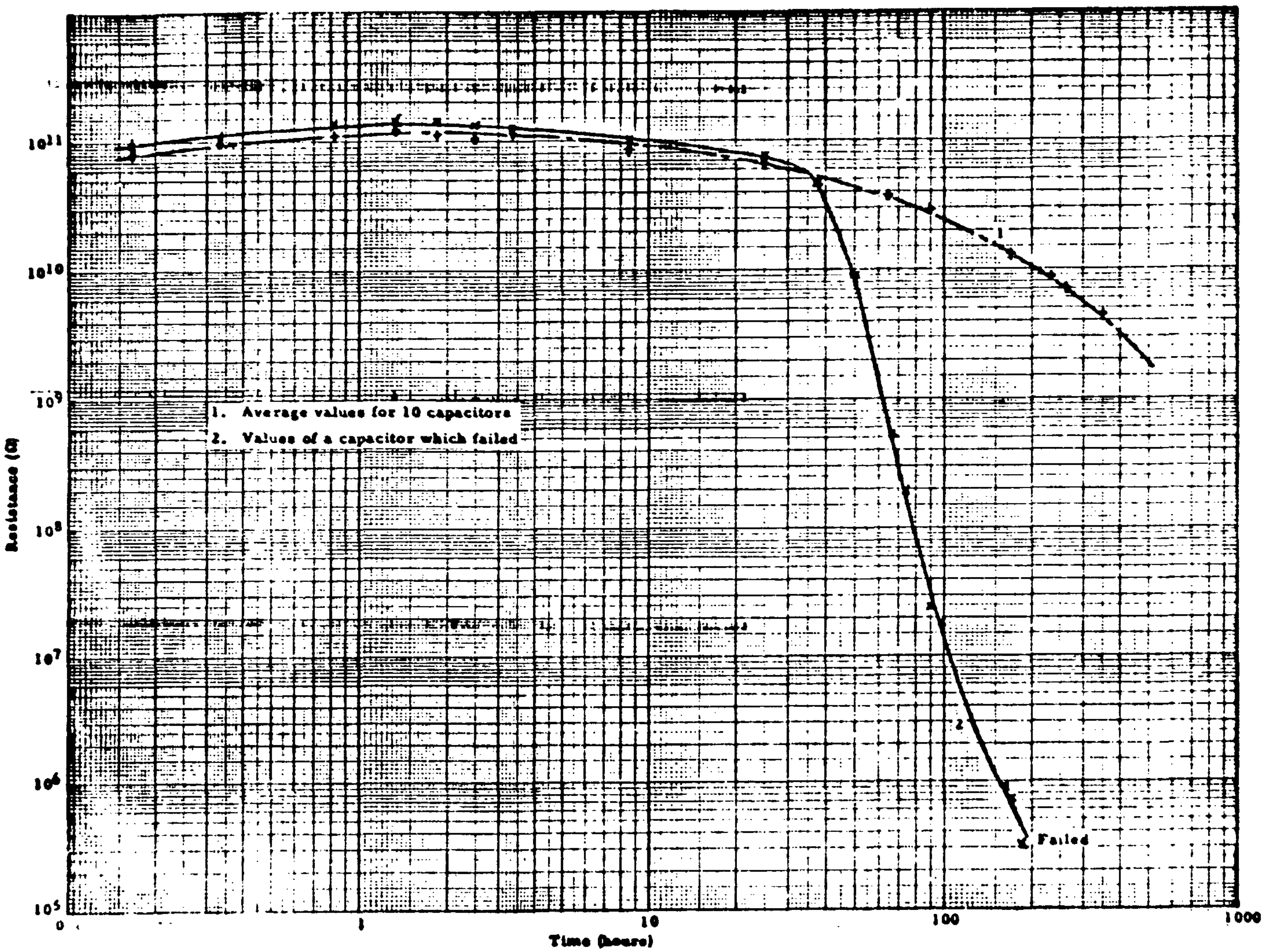
TYPICAL CURVE OF RESISTANCE VS TIME AT 150°C. 185 VDC (74 V/MIL) FOR A LOT D269 CAPACITOR (C67 MONOLYTHIC 0.01 uF Case Size I Capacitor)

Figure 45



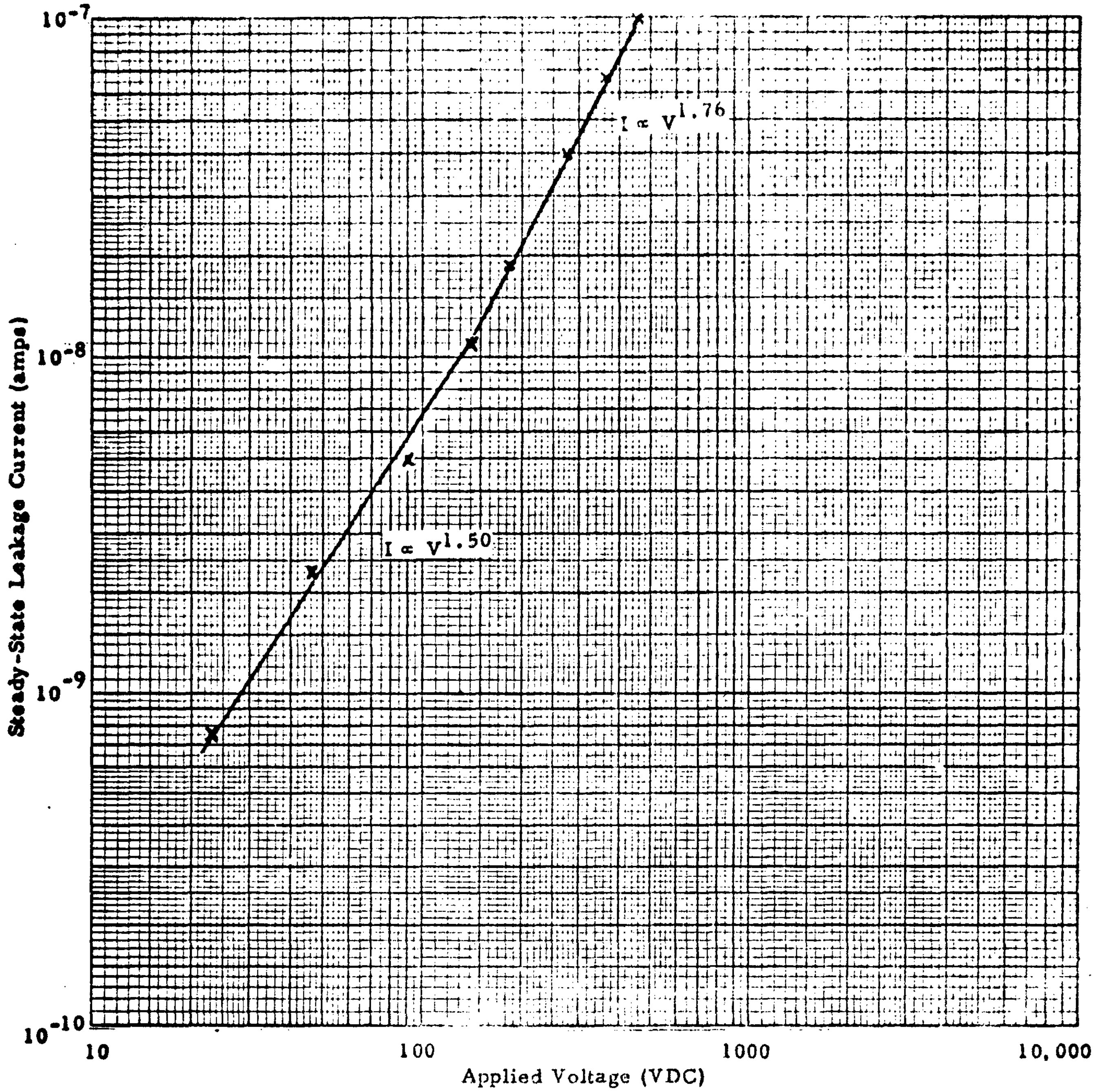
STEADY STATE LEAKAGE CURRENT VS APPLIED VOLTAGE AT 150°C FOR A LOT D128 CAPACITOR

Figure 46



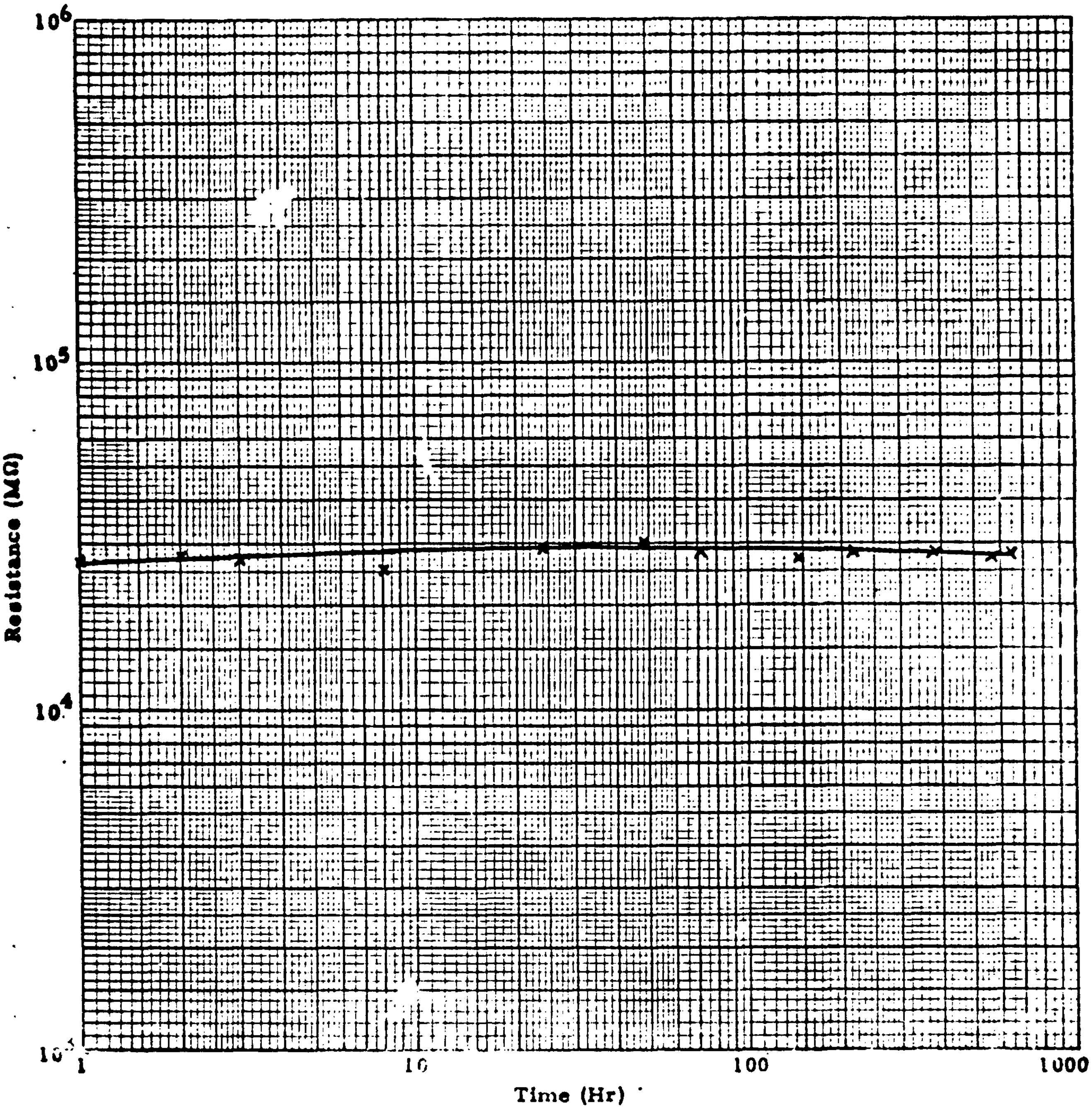
RESISTANCE VS TIME AT 195 VDC, 150°C
FOR 0.01 μF C67 CASE SIZE I IMPROVED MONOLYTHIC CAPACITORS (Lot D128)

Figure 47



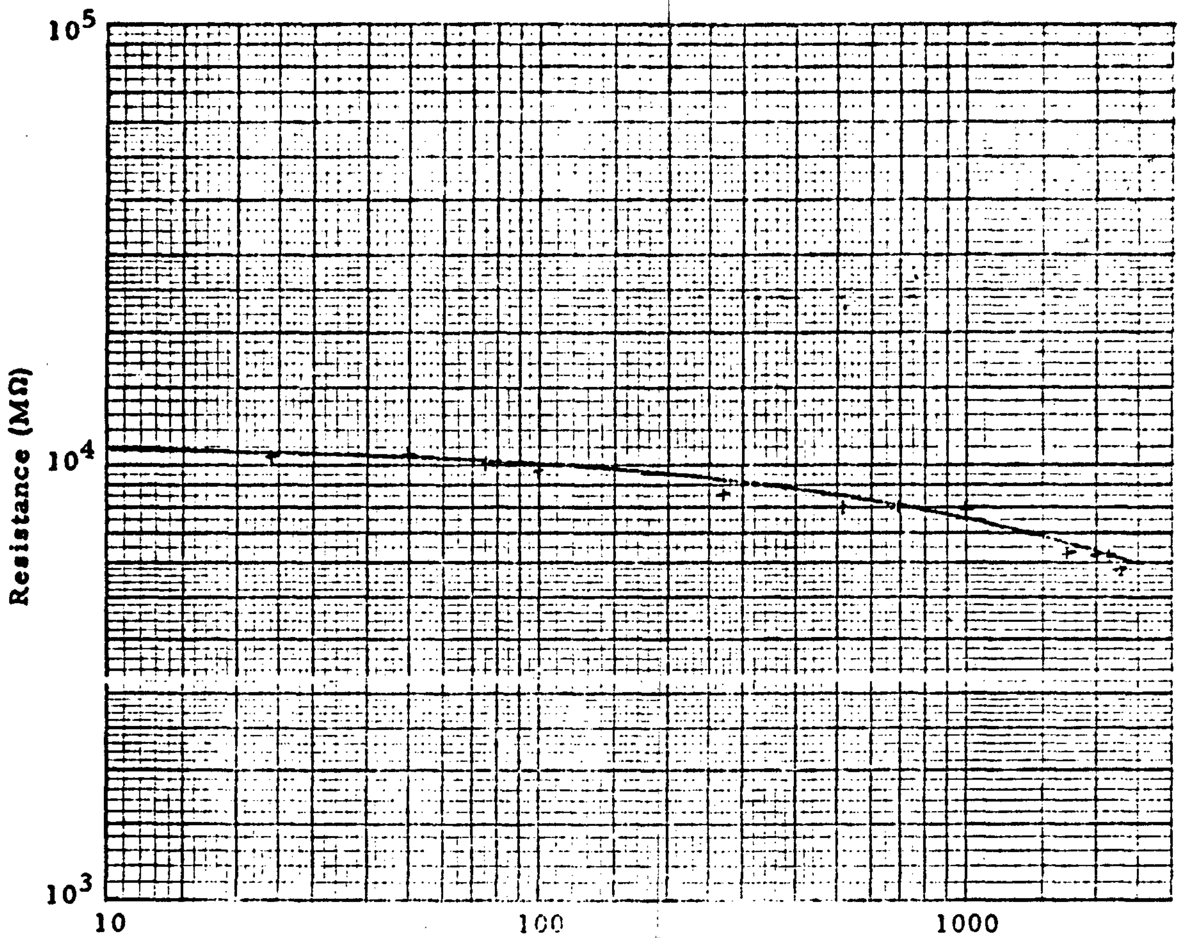
STEADY-STATE LEAKAGE CURRENT VS APPLIED VOLTAGE AT 150°C FOR A LOT X950A CAPACITOR (C67 ceramic, 0.001 in. dielectric layers, MONOLYTHIC, 0.047 μF, Case Size I)

Figure 48



TYPICAL CURVE OF RESISTANCE VS TIME AT 150°C, 95 VDC (95 V/MIL) FOR A [illegible] X950A CAPACITOR (C67 ceramic, 0.001 in. dielectric layers, MONOLITHIC, 0.047 μF, Case Size I)

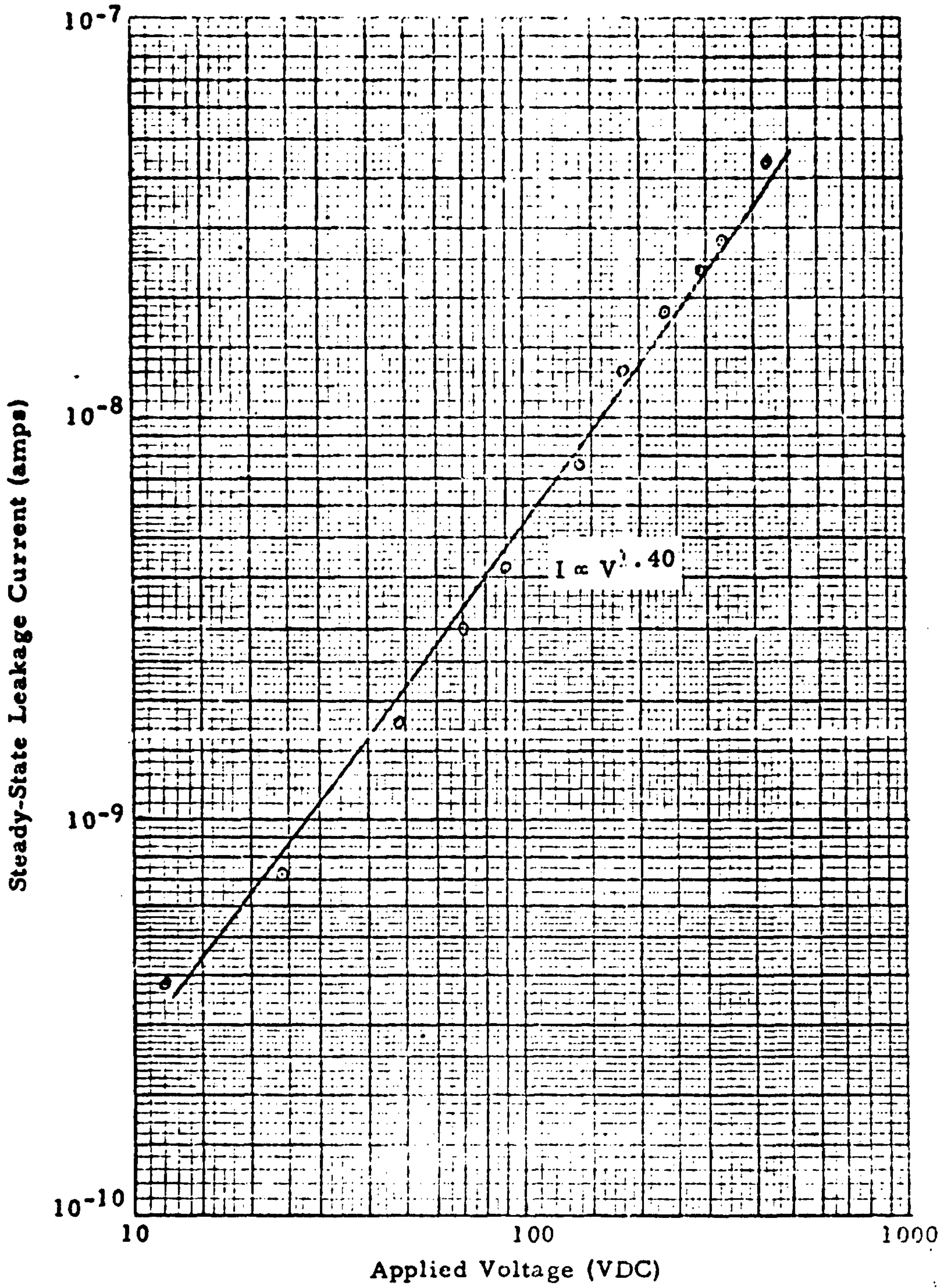
Figure 49



RESISTANCE VS TIME AT 150°C, 220 VDC (88 V/mil)
FOR 0.01 µF CASE SIZE I C67 MONOLYTHIC CAPACITORS (Lot 830)

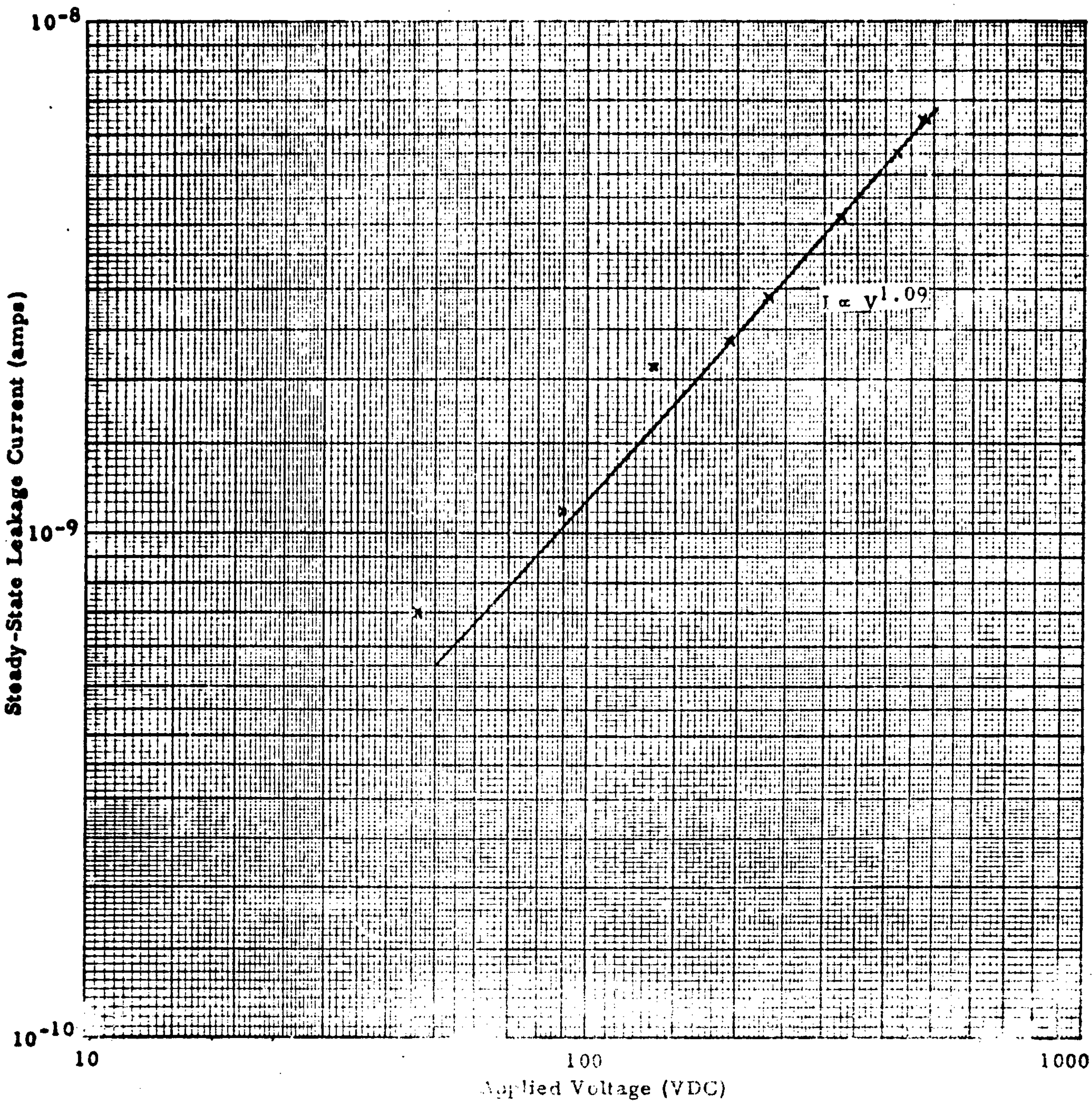
(Each point is the mean value for 4 units)

Figure



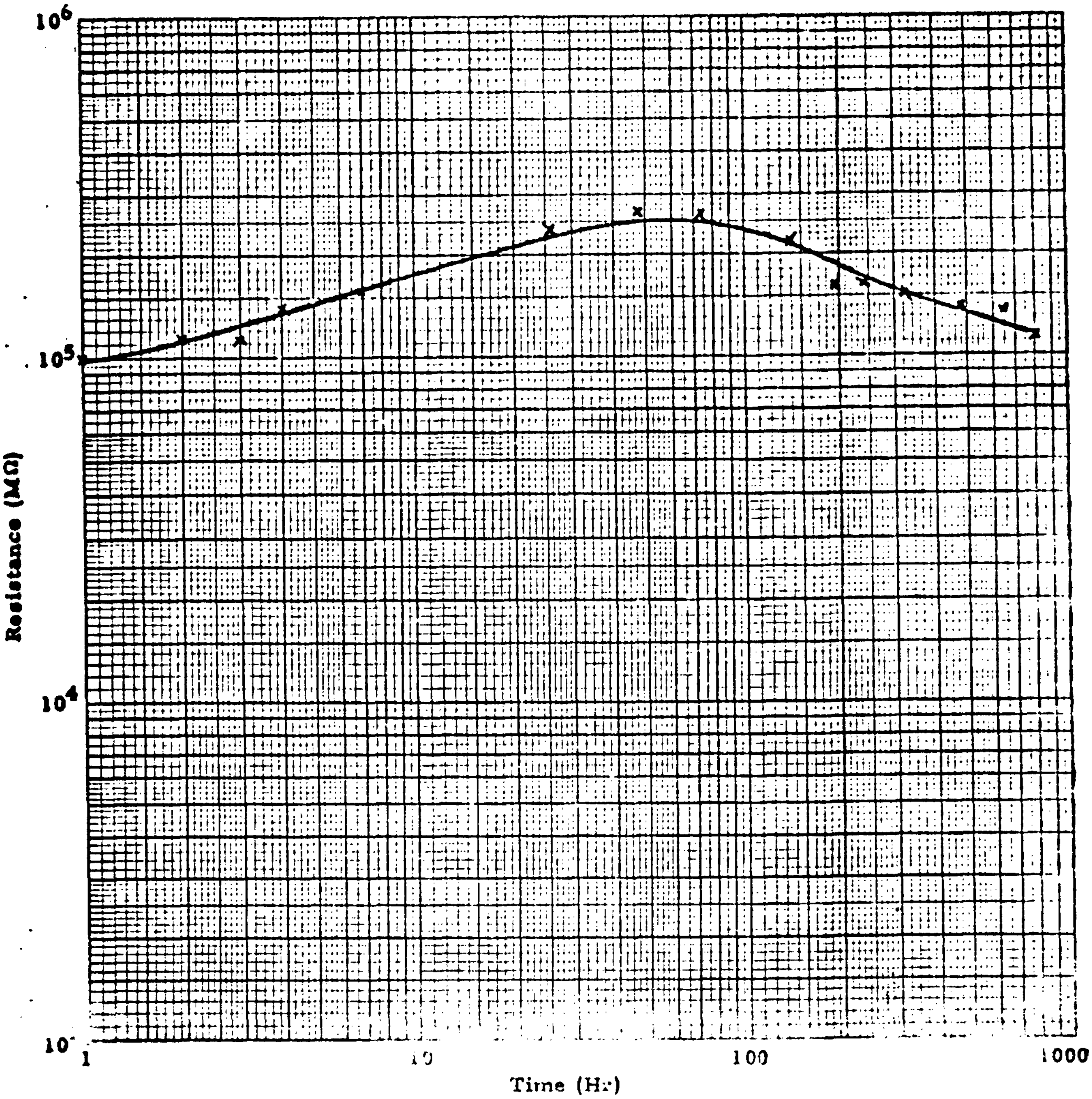
STEADY-STATE LEAKAGE CURRENT VS APPLIED VOLTAGE AT 150°C FOR A LOT 830 CAPACITOR

Figure 51



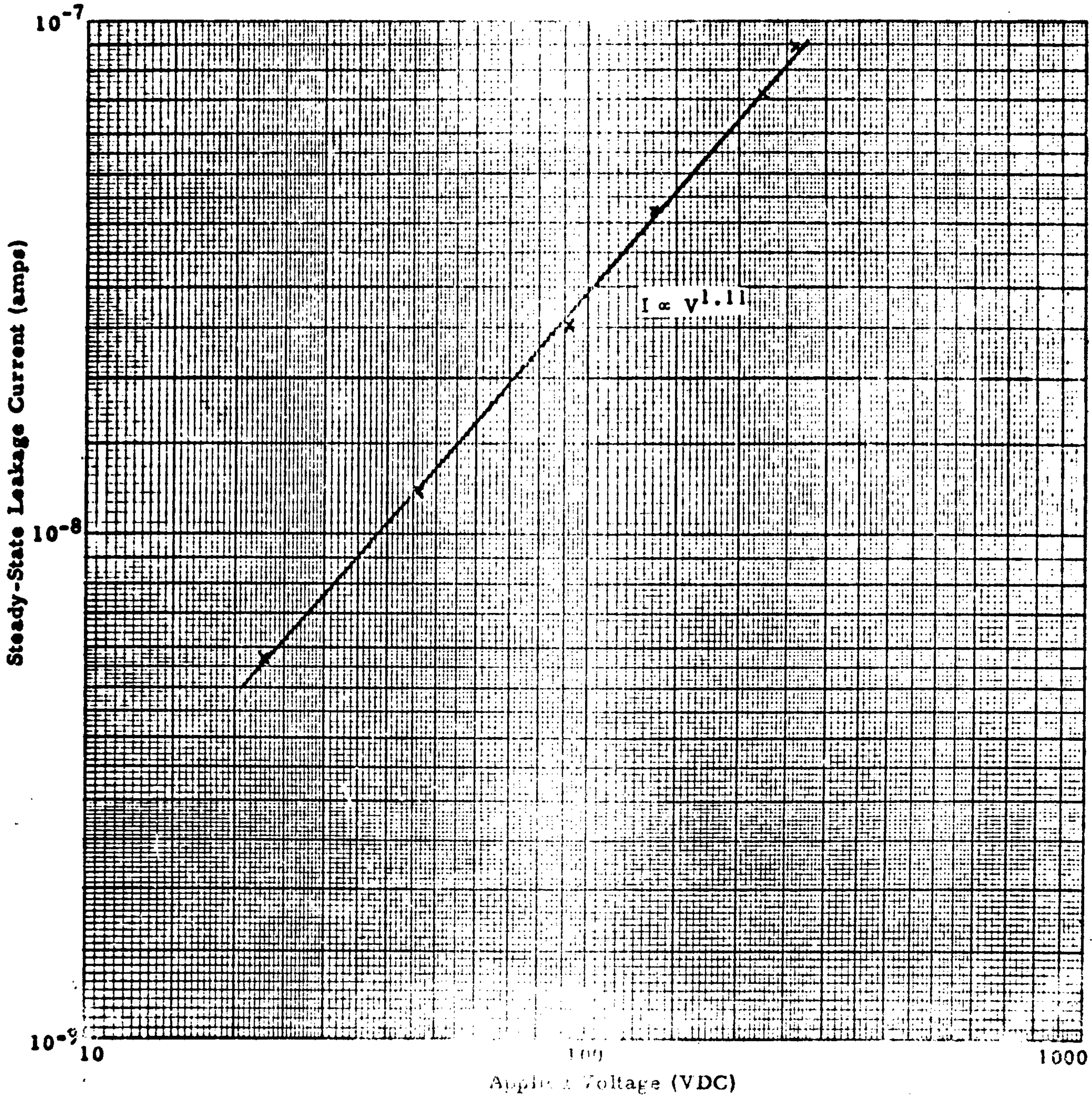
STEADY-STATE LEAKAGE CURRENT VS. APPLIED VOLTAGE
AT 150°C FOR A [illegible] CAPACITOR
(C25 ceramic, 0.001 in. dielectric layers, MONOLYTHIC, 0.0016 µF,
K = 36, TCC = HG, uncased size -- 0.24 in. x 0.18 in. x 0.030 in.)

Figure 52



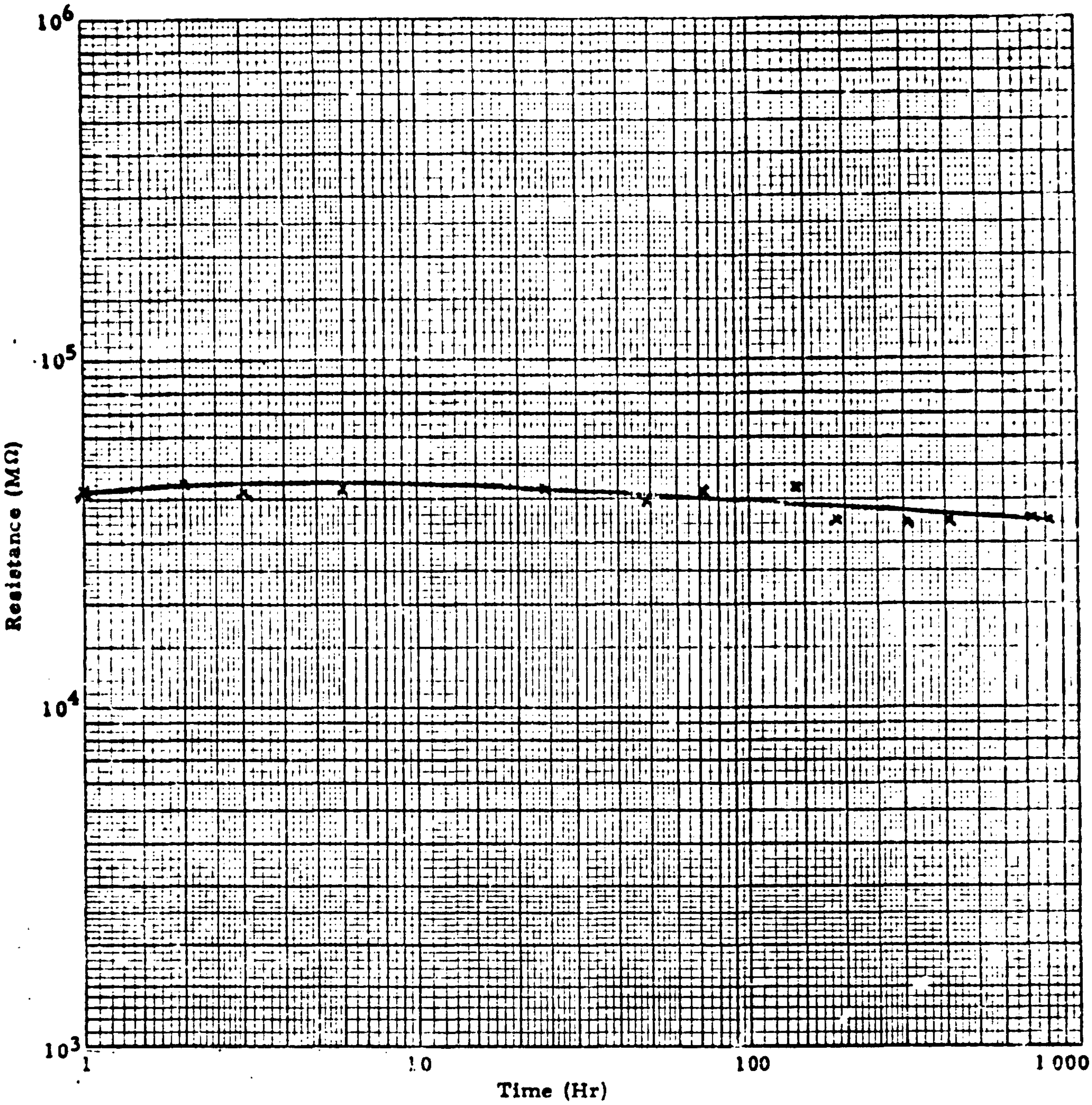
TYPICAL CURVE OF RESISTANCE [illegible] TIME AT [illegible]
95 VDC (95 V/MIL) [illegible] 51B CAP[illegible]
(C25 ceramic, MON[illegible], 0.0016 [illegible]F, K [illegible] 36, TC[illegible],
uncased size - 0.24 in. x 0.18 in. x 0.030 in.)

Figure 53



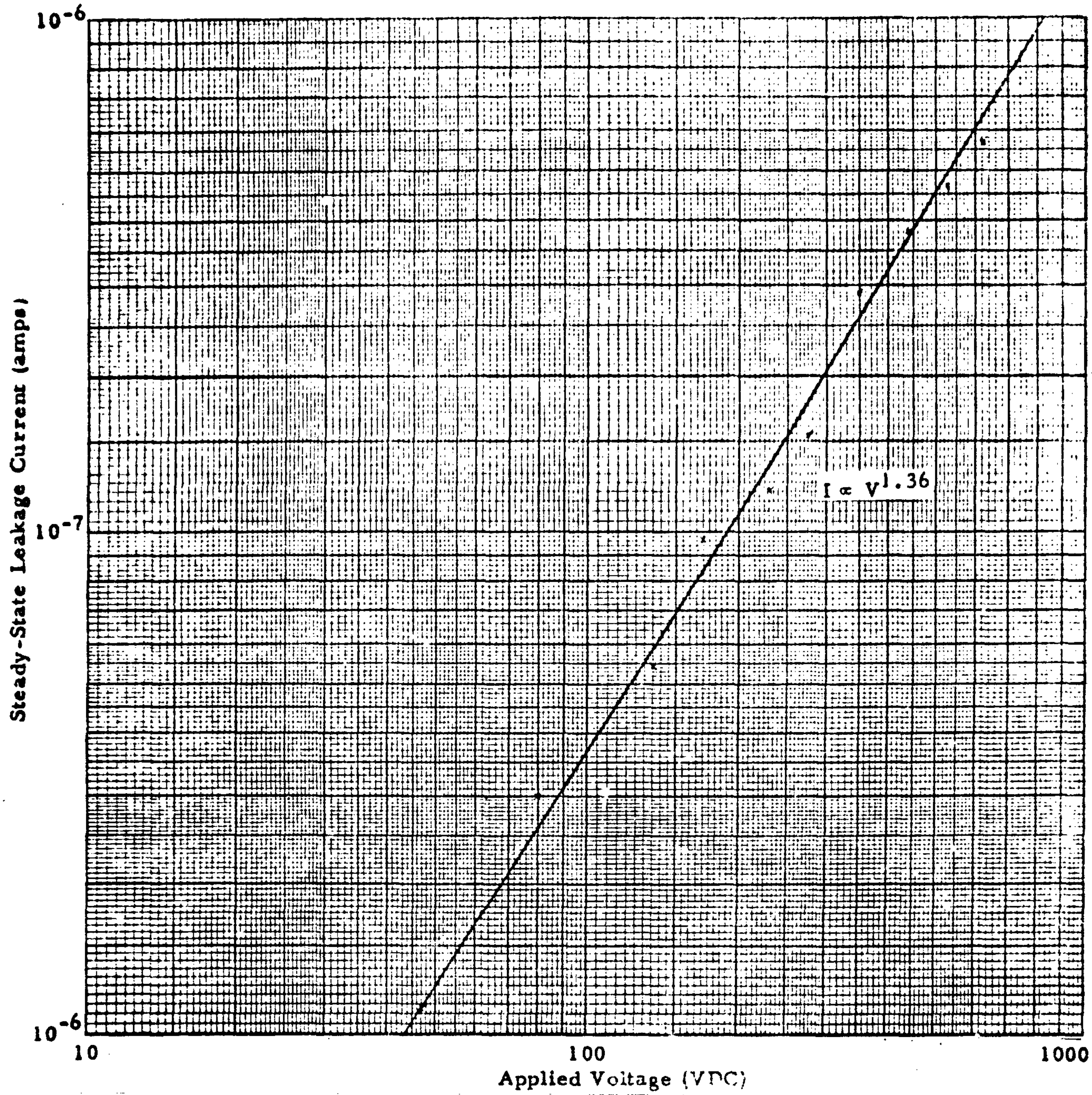
STEADY-STATE LEAKAGE [illegible] APPLIED [illegible]
AT 150°C [illegible] APACIT[illegible]
(C75 ceramic, MO[illegible] pF, K = 115, TCC = [illegible]
uncased size – 0.24 in. x 0.18 in. x 0.030 in.)

[illegible]



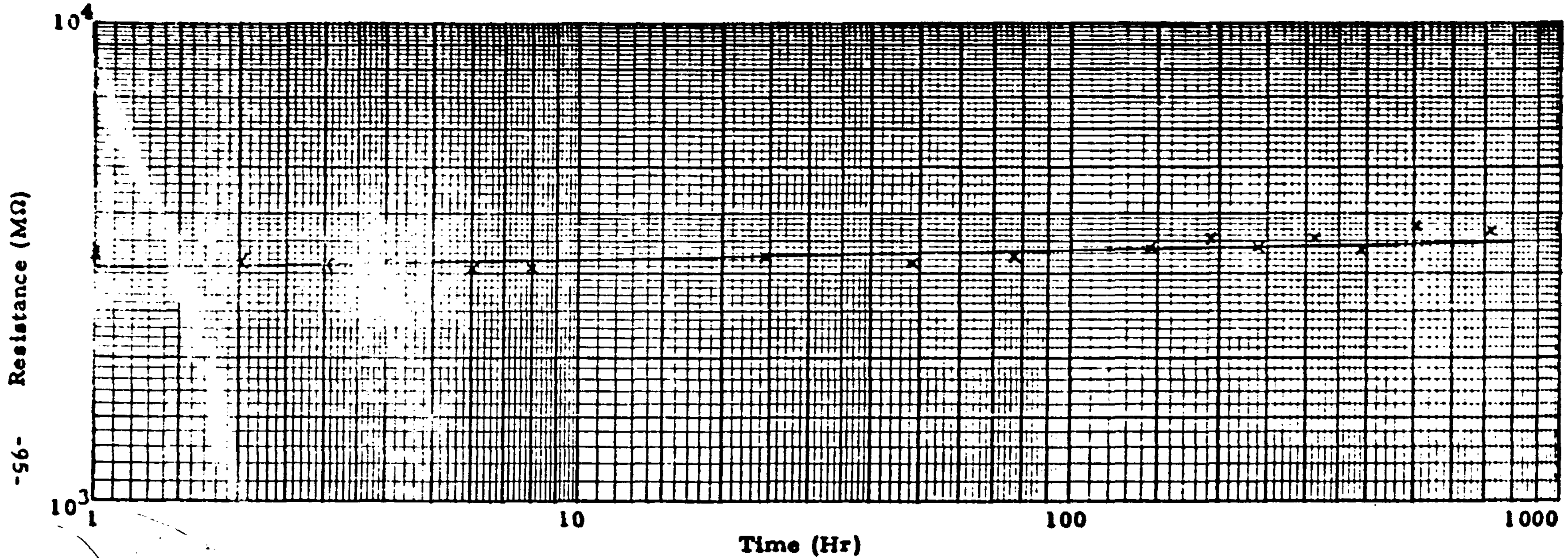
RESISTANCE VS TIME AT 150°C, 95 VDC (79 V/MIL)
FOR LOT X977B CAPACITORS
(C75 ceramic, MONOLYTHIC, 0.004 μF, K = 115, TCC = UJ,
uncased size – 0.24 in. x 0.18 in. x 0.030 in.)
(Each point is mean value of four units)

Figure 55



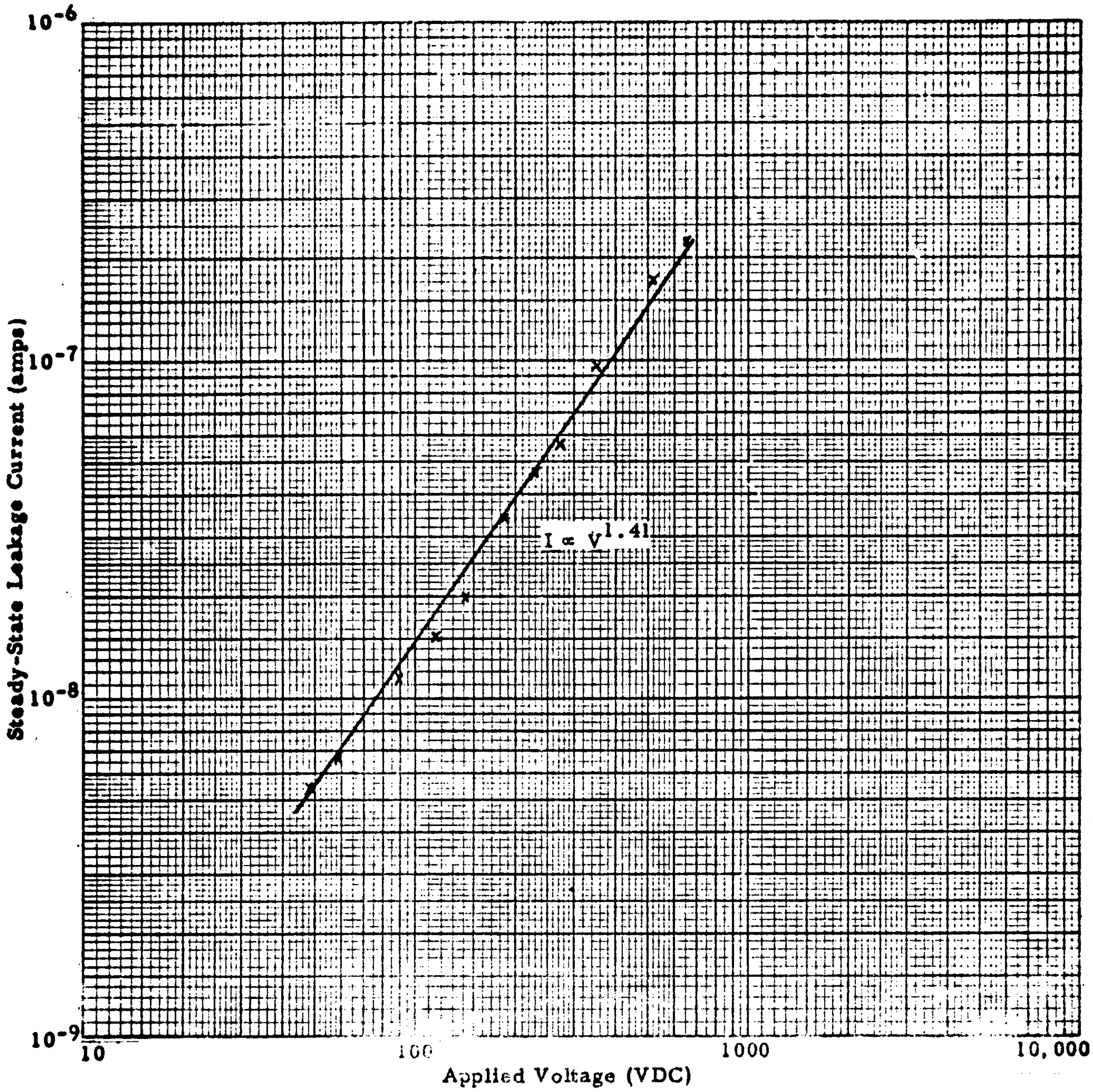
STEADY-STATE LEAKAGE CURRENT VS APPLIED VOLTAGE
AT 150°C FOR A LOT X930B CAPACITOR
(C73 ceramic, 0.0025 in. dielectric layers, MONOLYTHIC, 0.05 μF,
K = 1500, TCC = BX, uncased size – 0.40 in. x 0.22 in. x 0.045 in.)

Figure 56



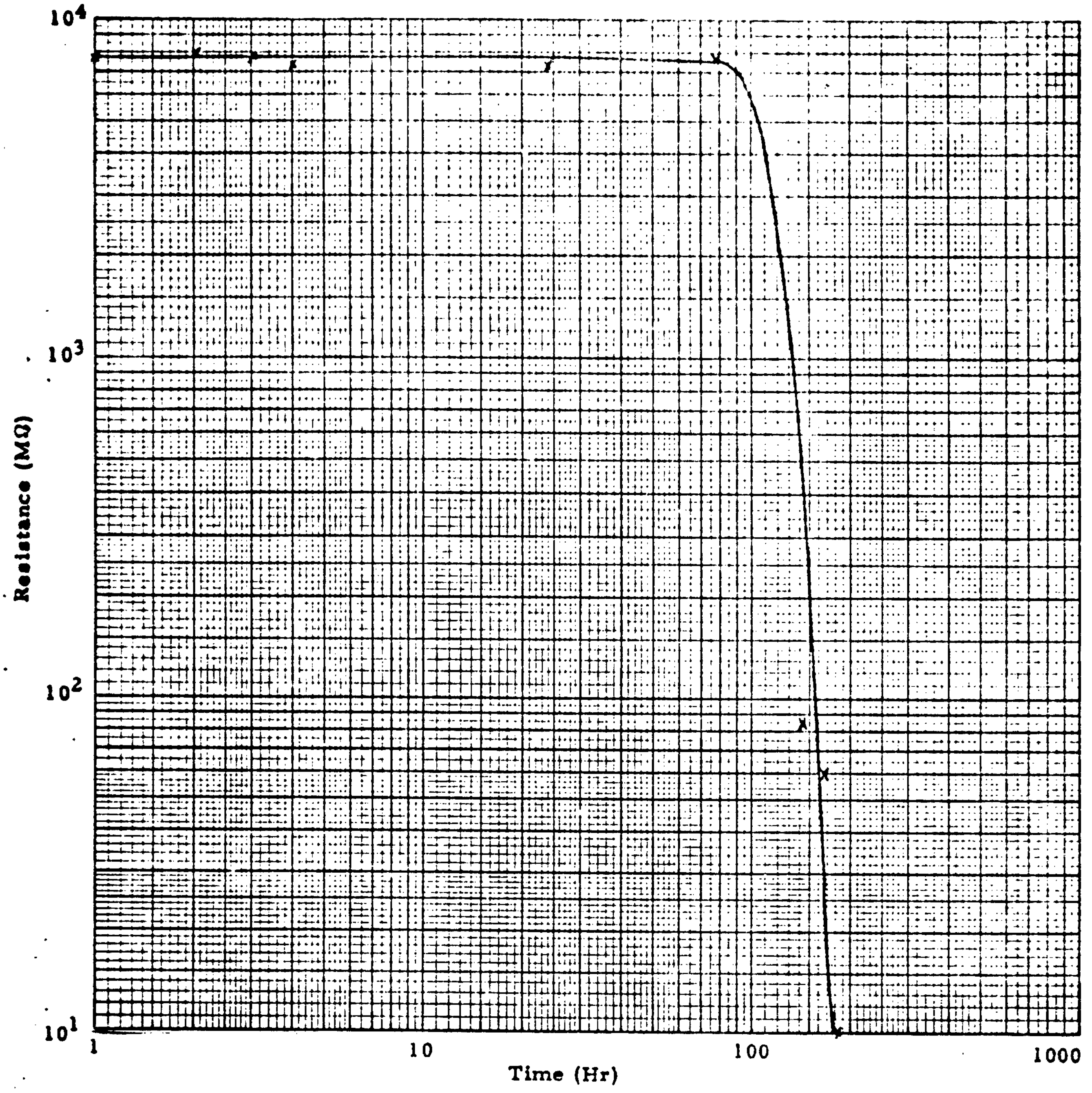
RESISTANCE VS TIME AT 150°C, 185 VDC (74 V/MIL)
FOR LOT X930B CAPACITORS
(C73 ceramic, MONOLYTHIC, 0.05 μF, K = 1500, TCC = BX,
uncased size – 0.40 in. x 0.22 in. x 0.045 in.)
(Each point is mean value of six units)

Figure 57



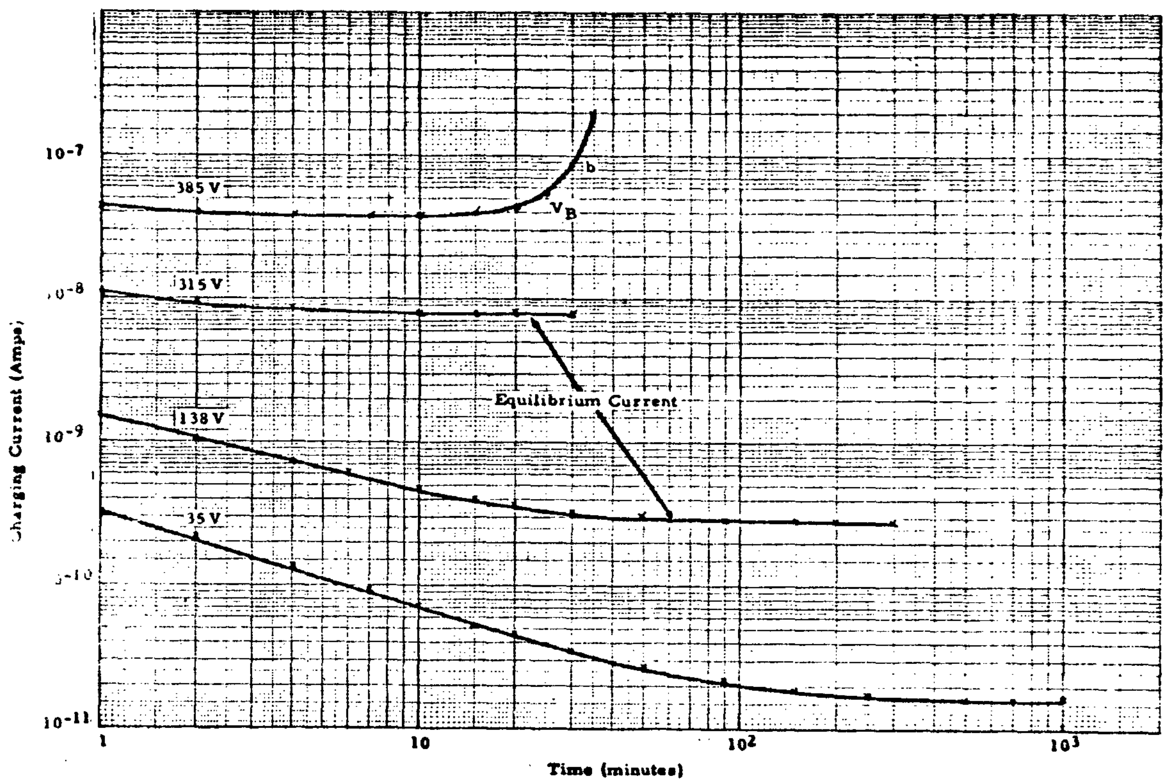
STEADY-STATE LEAKAGE CURRENT VS APPLIED VOLTAGE AT 150°C FOR A [illegible] X958B CAPACITOR
(C73 ceramic, 0.0025 in. dielectric layers, MONOLYTHIC, 0.02 μF, K = 1500, TCC = 5X, uncased size – 0.40 in. x 0.22 in. x 0.045 in.)

Figure 58



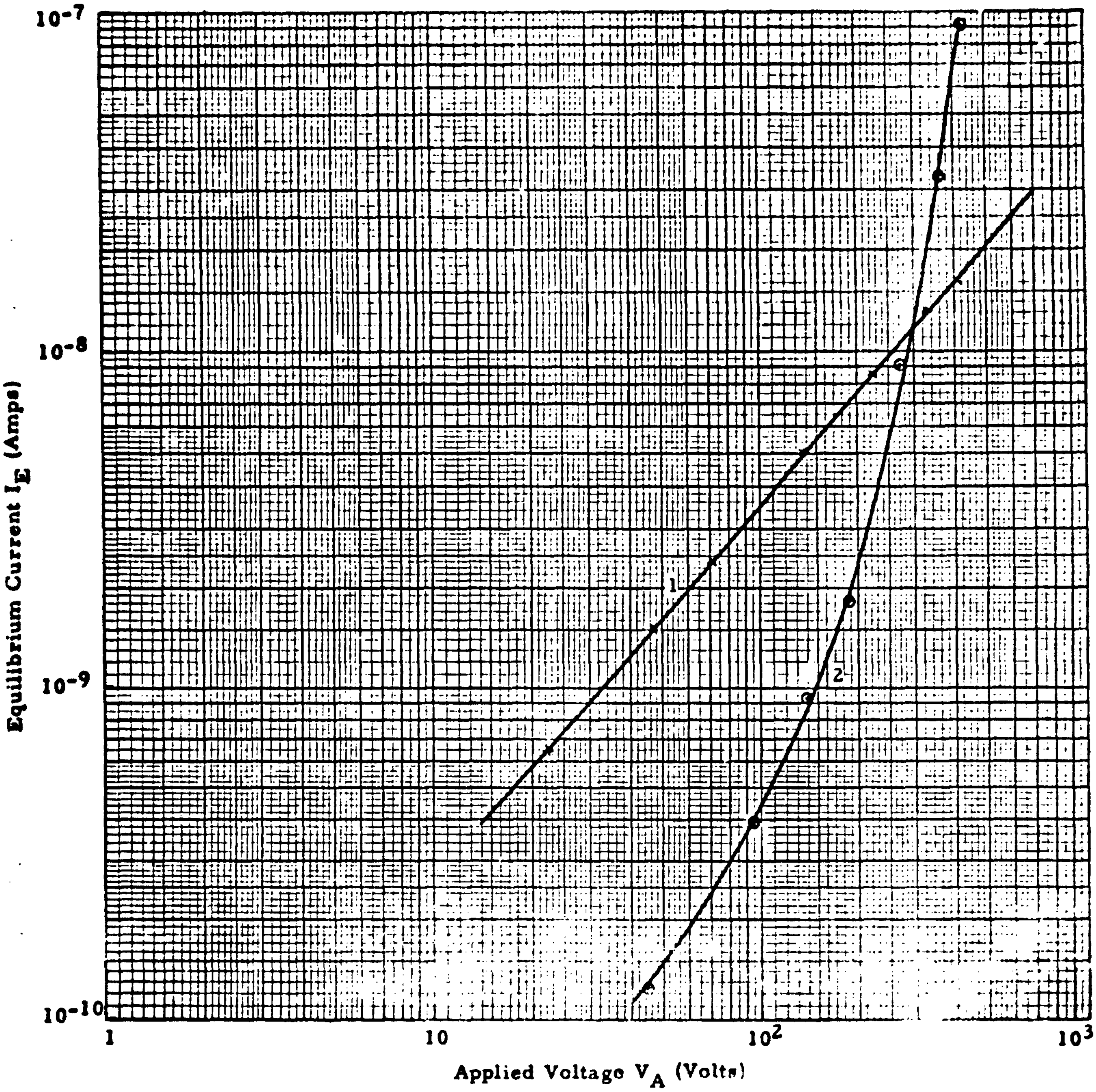
TYPICAL CURVE OF RESISTANCE VS TIME AT 150°C, 190 VDC (76 V/MIL) FOR LOT X9[illegible] CAPACITORS (C73 ceramic, MONOLYTHIC, 0.02 µF, [illegible] TCC = BX, uncased size – 0.40 in. x 0.22 in. x 0.045 in.)

Figure 59



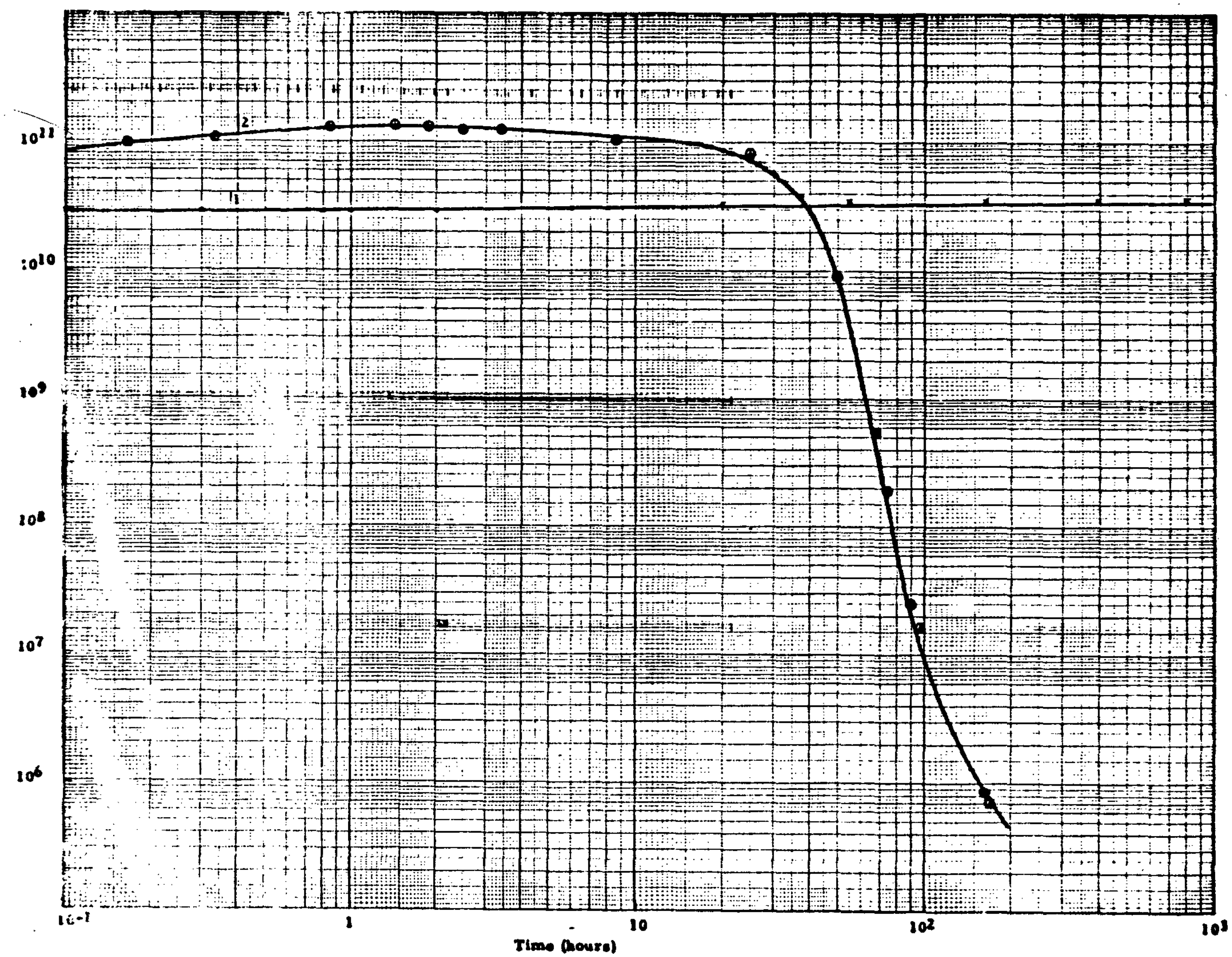
TYPICAL CHARGING-CURRENT CHARACTERISTICS AT 150°C
2.5 MIL DIELECTRIC LAYER

Figure 60



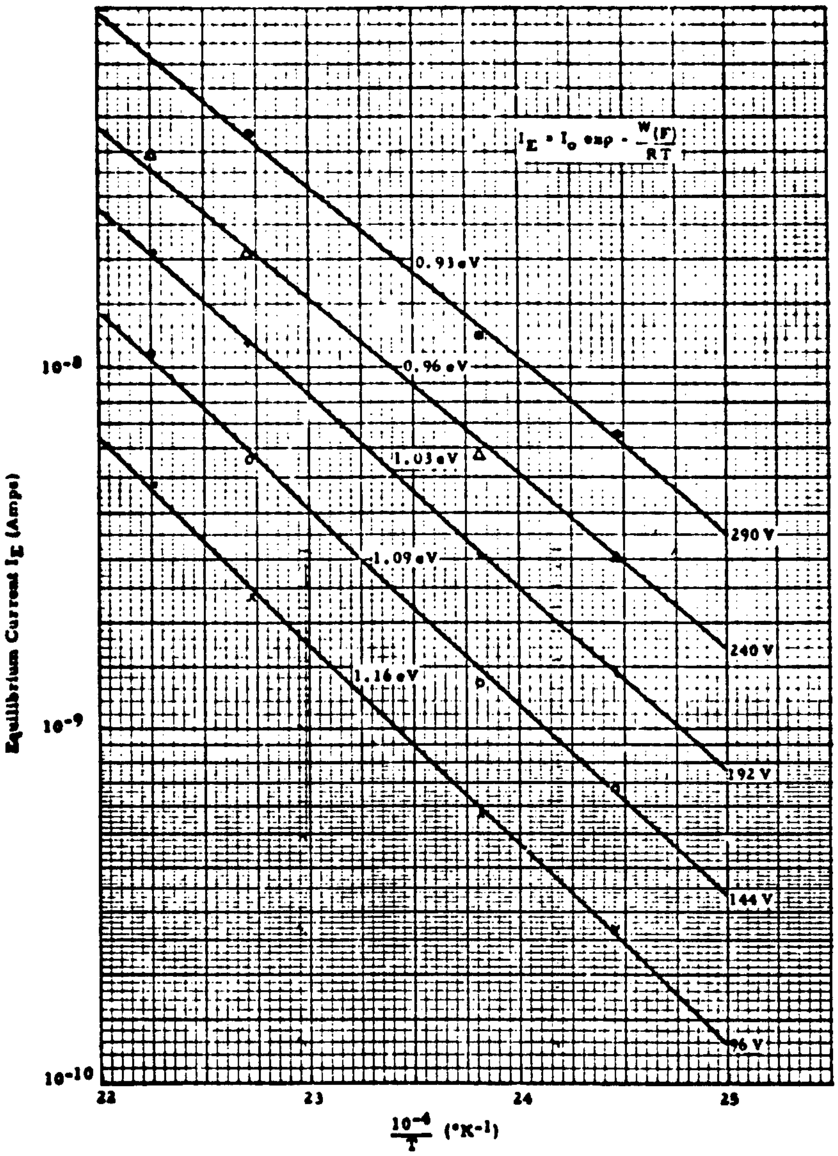
I_E VS V_A CHARACTERISTICS [illegible] RELIABLE [illegible]ACITOR [illegible]
AND AN [illegible]LIABLE CAPACITOR 2
150°C 2.5 MIL DIELECTRIC

Figure 51



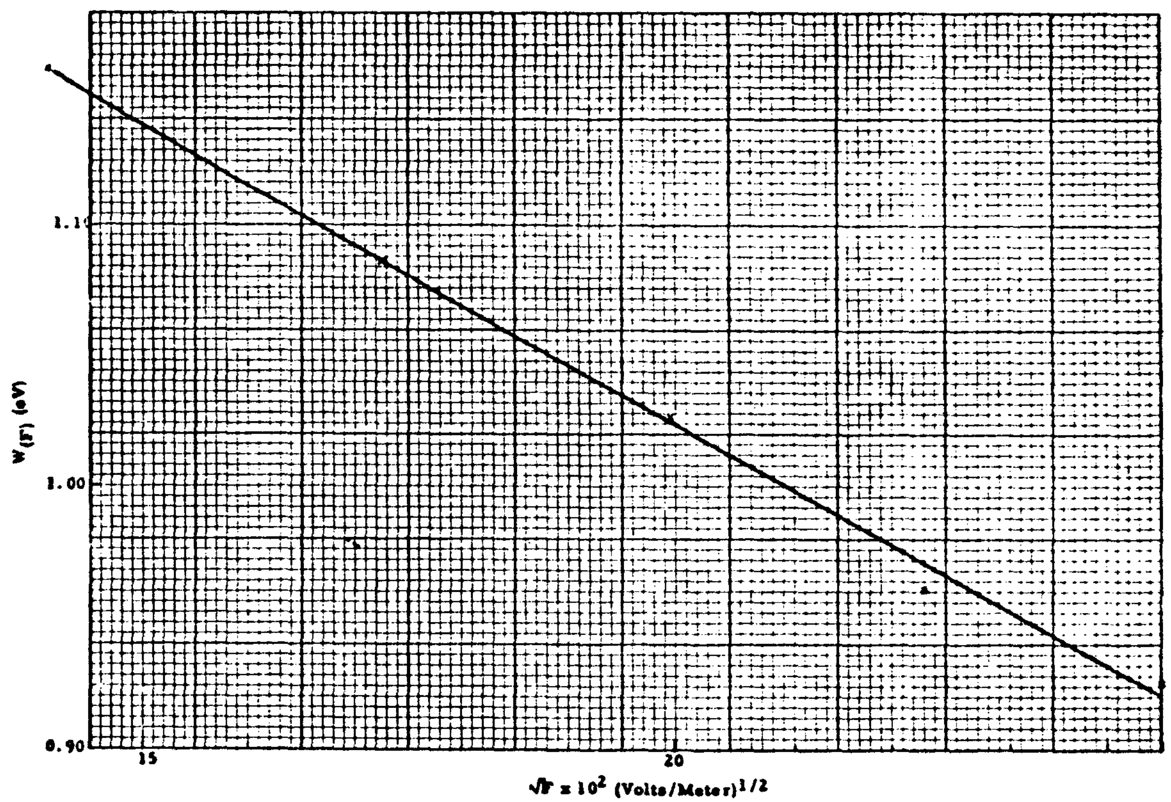
LIFE TEST CHARACTERISTICS OF UNITS 1 AND 2 (FIGURE 61)
150°C AND 76 VOLTS/MIL

Figure 62



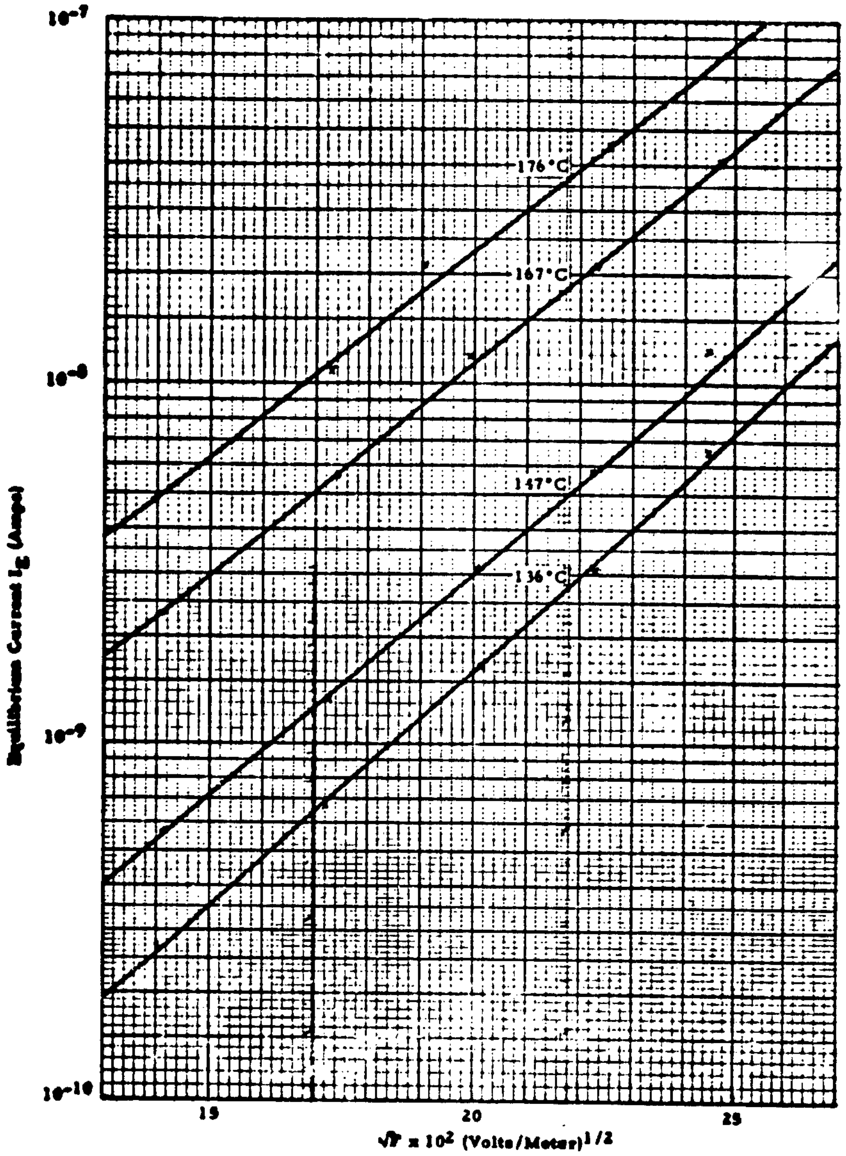
ARRHENIUS PLOTS FOR A 1.9 MIL DIELECTRIC LAYER

Figure 63



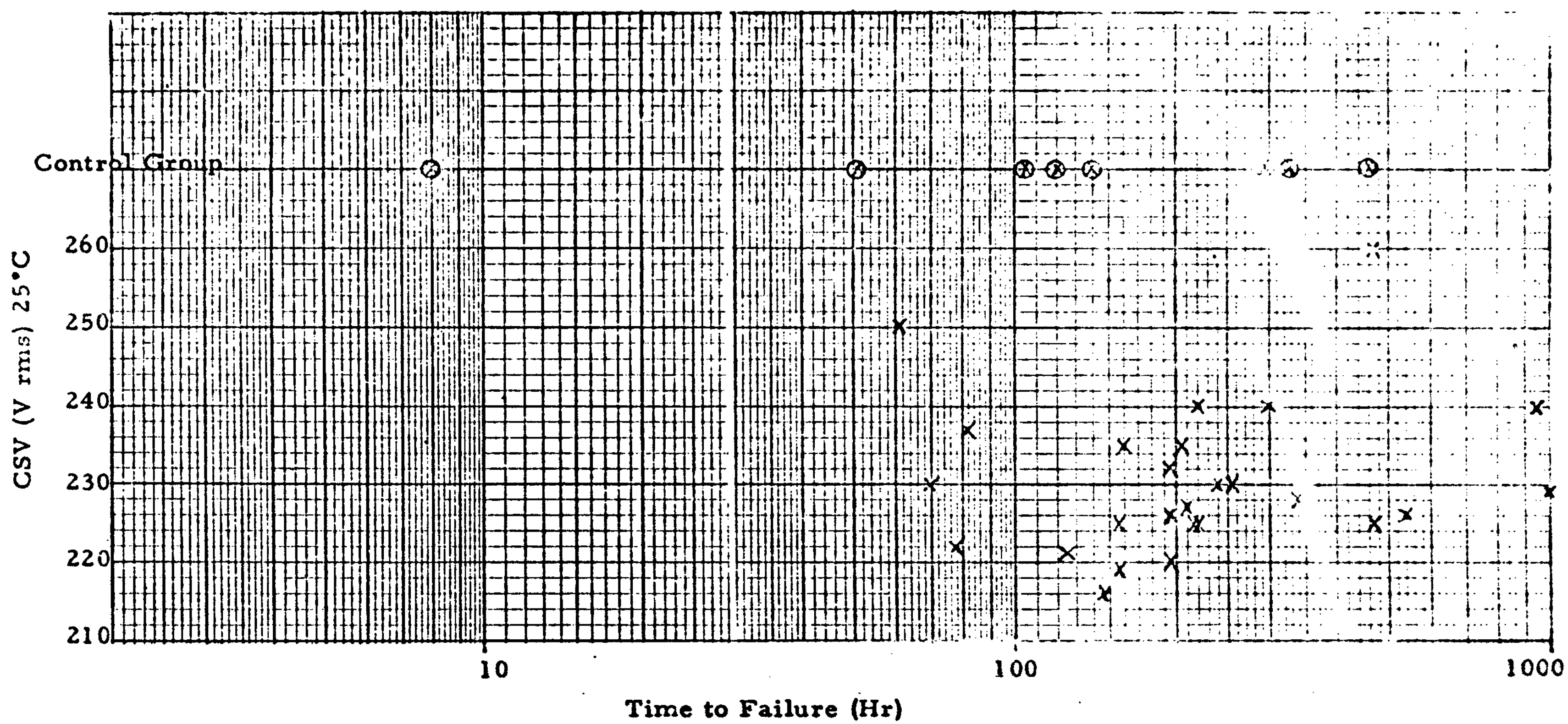
$W_{(F)} = (W_o - B\sqrt{F})$

Figure 64



$\log I_E \propto B\sqrt{F}$

Figure 65



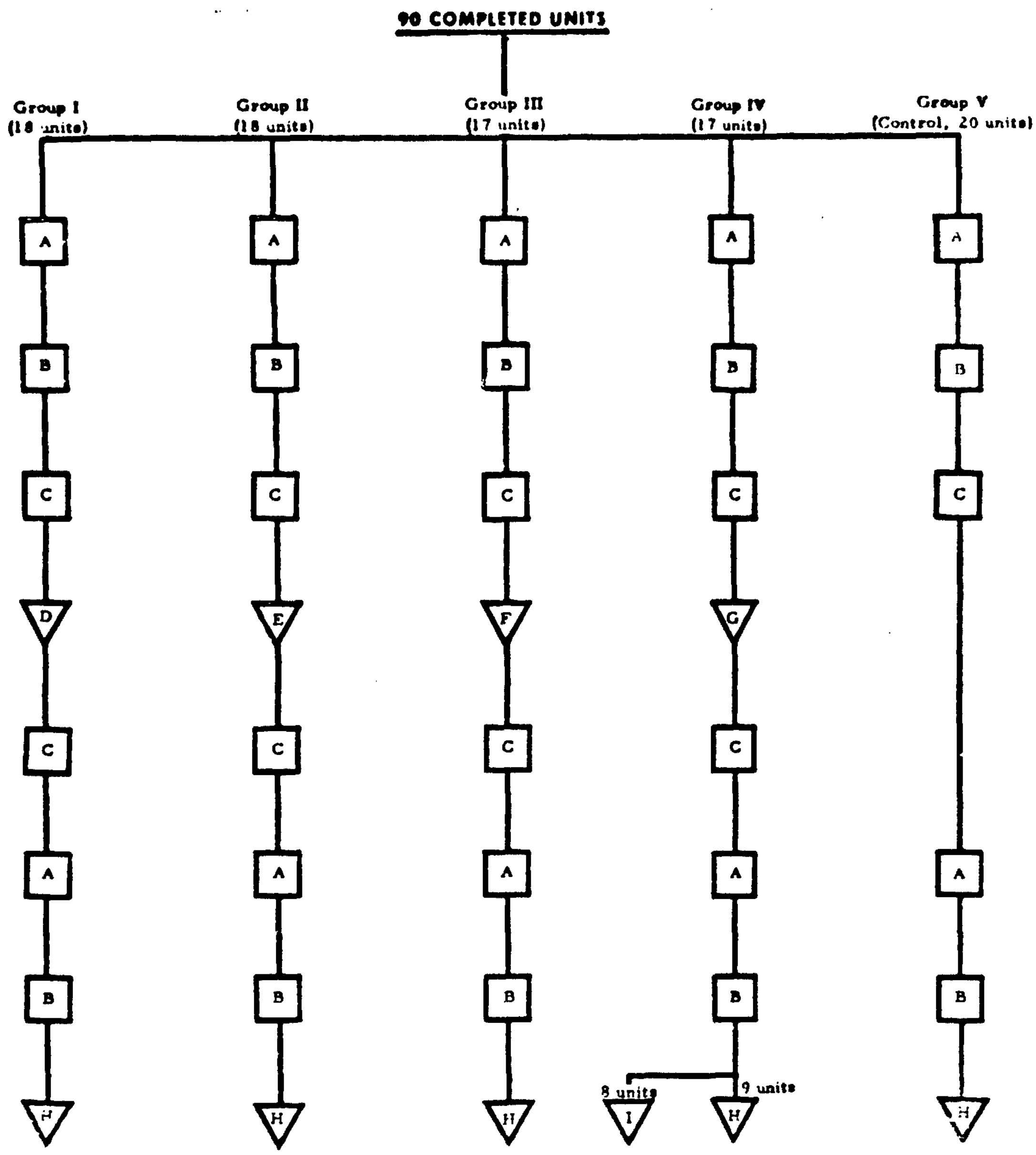
RELATIONSHIP BETWEEN
CORONA START VOLTAGE (CSV)
AND TIME TO FAILURE
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITORS (~11,000 μμF)

Life test conditions: 75 VDC/mil, 150°C)

(Definition of Failure: electrical resistance <100 MΩ at life test conditions)

Dielectric Thickness: 0.0025 in.

Figure 66



Measurement

Test

KEY: A - Measurement	:	Capacitance, dissipation factor, at 1 kHz/sec and 25°C
B - Measurement	:	25°C resistance at +100 VDC and at -100 VDC
C - Measurement	:	150°C resistance at +100 VDC and at -100 VDC
D - Test	:	100 V rms, (60 cps), [illegible]°C for 50 hr
E - Test	:	175 V rms, (60 cps), 150°C for [illegible]
F - Test	:	[illegible] rms, (60 cps), 150°C [illegible]
G - Test	:	225 VDC, 150°C for 50 [illegible]
H - Life Test	:	+190 VDC, 150°C
I - Life Test	:	-190 VDC, 150°C

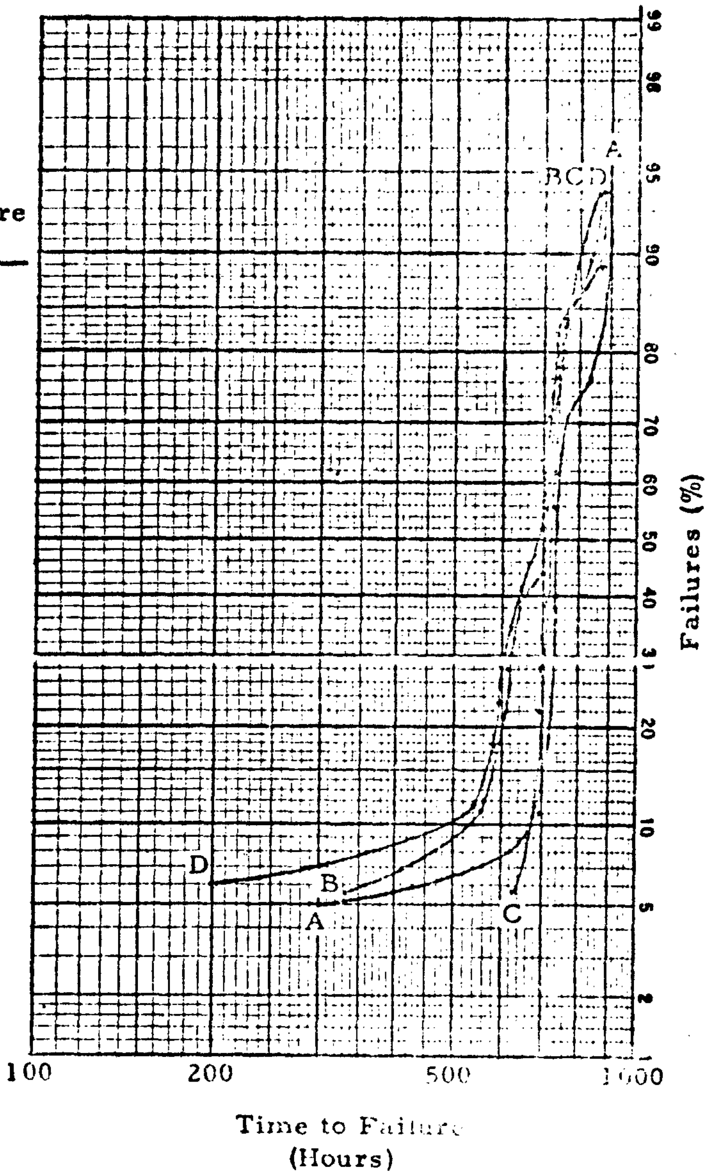
(Dielectric Thickness of these units is 0.0025 in.)

SEQUENCE OF TESTING

FIGURE 67

Curve	Group	Life Test Voltage (VDC)	Time to 50% Failure (Hours)
A	V	+190	730
B	I	+190	710
C	II	+190	720
D	III	+190	690

Test Conditions: 150°C, 190 VDC
(75 VDC/mil)



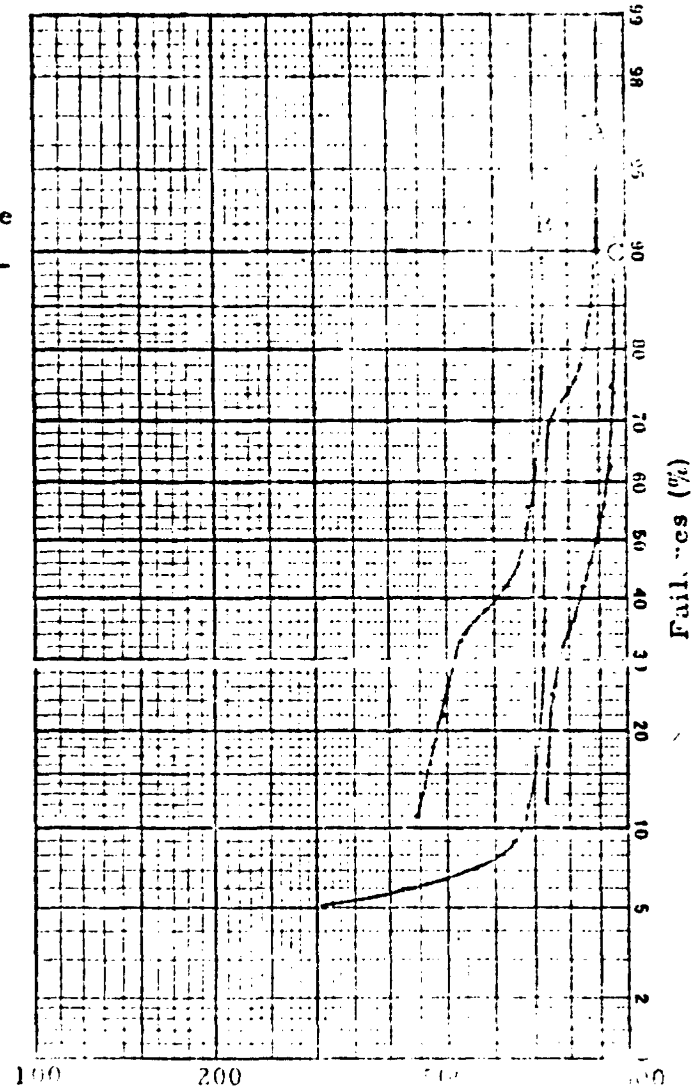
NUMBER OF FAILURES VS TIME TO FAILURE

(Definition of Failure: electrical resistance <100 MΩ at test conditions)

Figure 68

Curve	Group	Life Test Voltage (VDC)	Time to 50% Failure (Hours)
A	V	+190	730
B	IV	+190	680
C	IV	-190	890

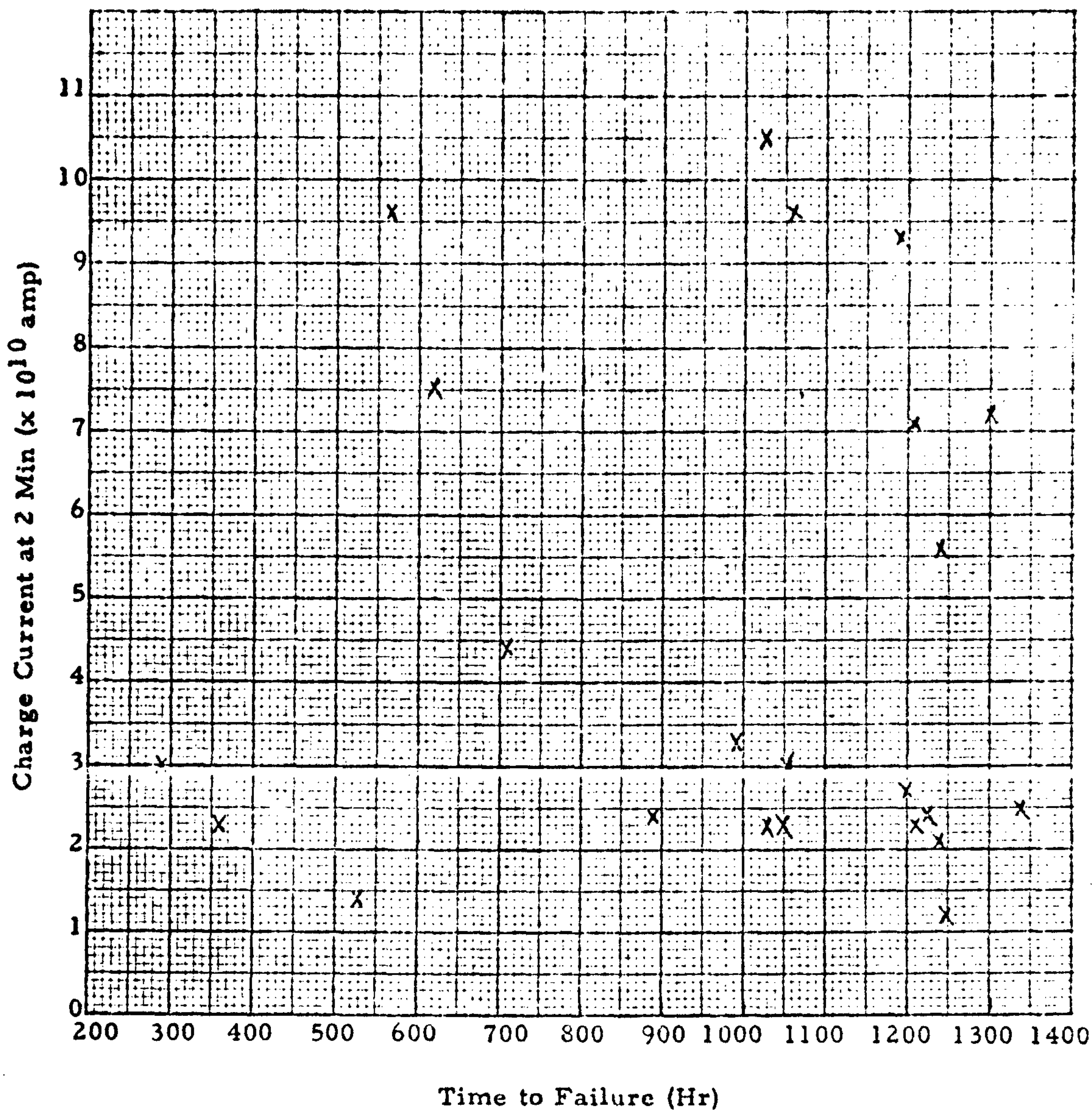
Test Conditions: 150°C, 190 VDC (75 VDC/mil)



NUMBER OF FAILURES ... TIME TO ...

(Definition of Failure: electrical resistance <100 MΩ at test conditions)

Figure 69



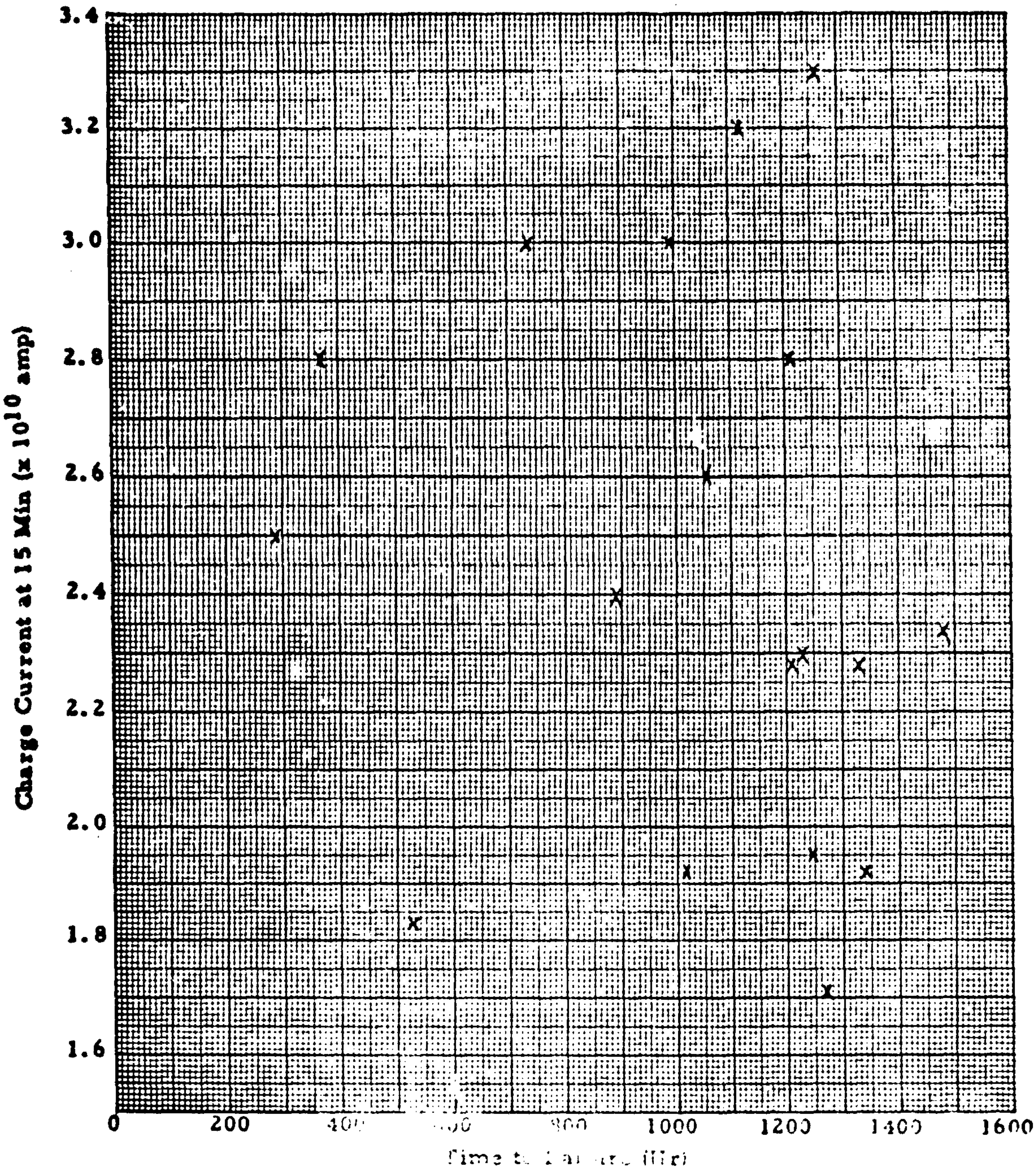
RELATIONSHIP BETWEEN CHARGE CURRENT AT 2 MIN
AND TIME TO FAILURE
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITORS (6000 $\mu\mu F$)

(Charge conditions: 150°C, 225 VDC)

(Definition of Failure: electrical resistance <10
at life test conditions of 150°C, 190 VDC)

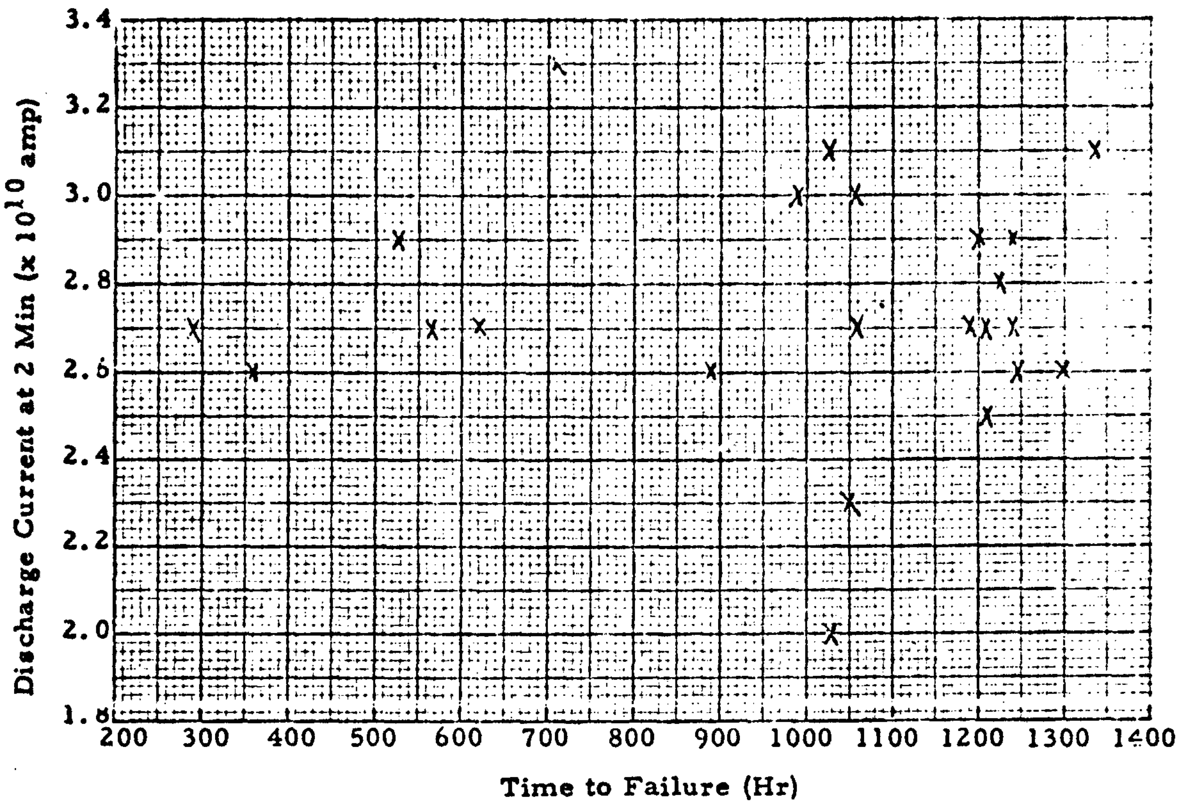
(Dielectric thickness: 0.0025 in.)

Figure 70



RELATIONSHIP BETWEEN CHARGE CURRENT AT 15 MIN
AND TIME TO FAILURE
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITORS (6000 [illegible])
(Charge Conditions: 225 VDC, 150°C;
Test Conditions: [illegible] VDC, 150°C)
(Definition of [illegible] electrical resistance <10 MΩ)

Figure 71

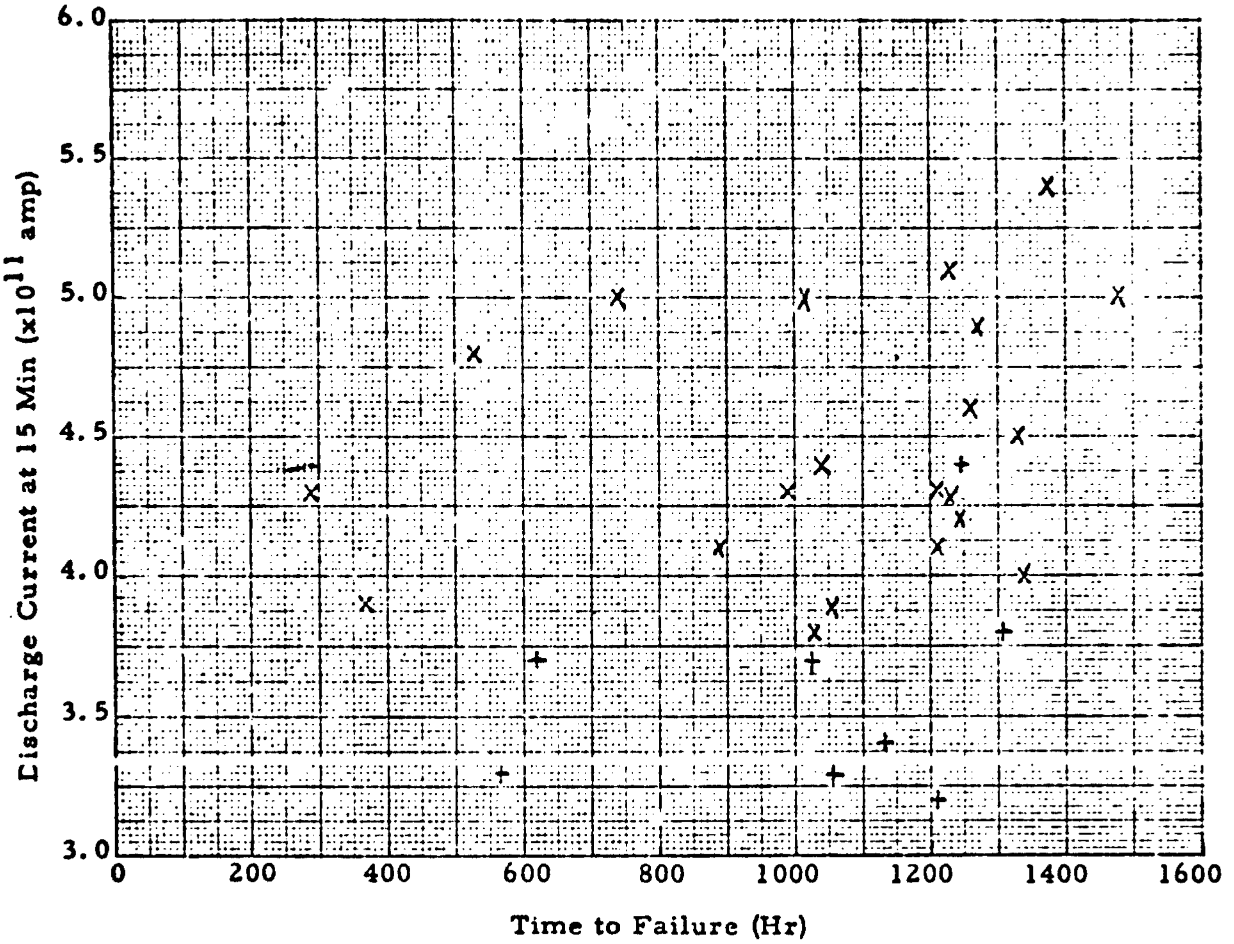


RELATIONSHIP BETWEEN DISCHARGE CURRENT AT 2 MIN
AND TIME TO FAILURE
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITORS (6000 μμF)

(Charge Conditions: 150°C, 225 VDC, 15 min)

(Definition of Failure: electrical resistance <10 MΩ
at life test conditions of 150°C, 190 VDC)

Figure 72

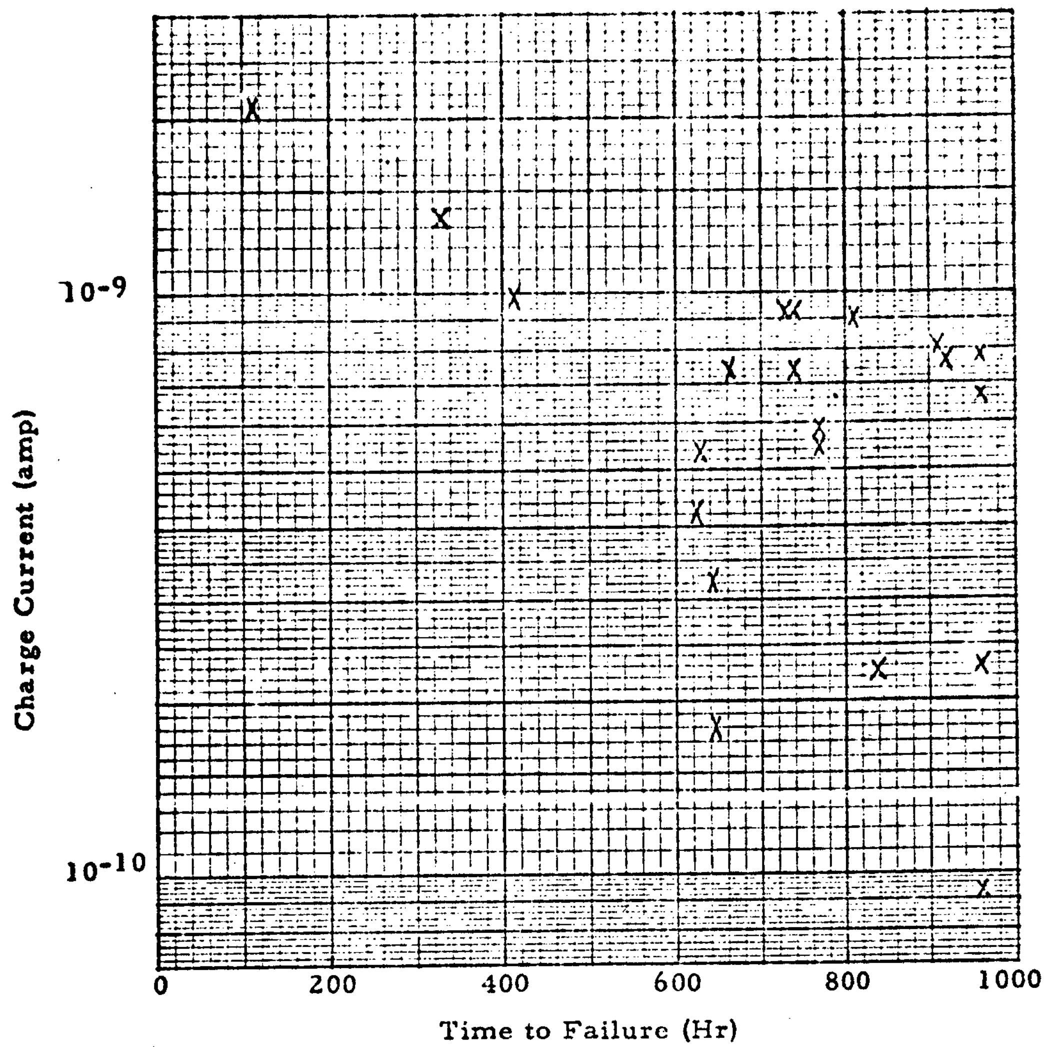


RELATIONSHIP BETWEEN DISCHARGE CURRENT AT 15 MIN
AND TIME TO FAILURE
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITORS (6000 $\mu\mu$F)

(Charge Conditions: x units - 225 VDC, 150°C, 15 min
+ units - 225 VDC, 150°C, 5 min;
Test Conditions: 190 VDC, 150°C)

(Definition of Failure: electrical resistance < 10 MΩ)

Figure 73

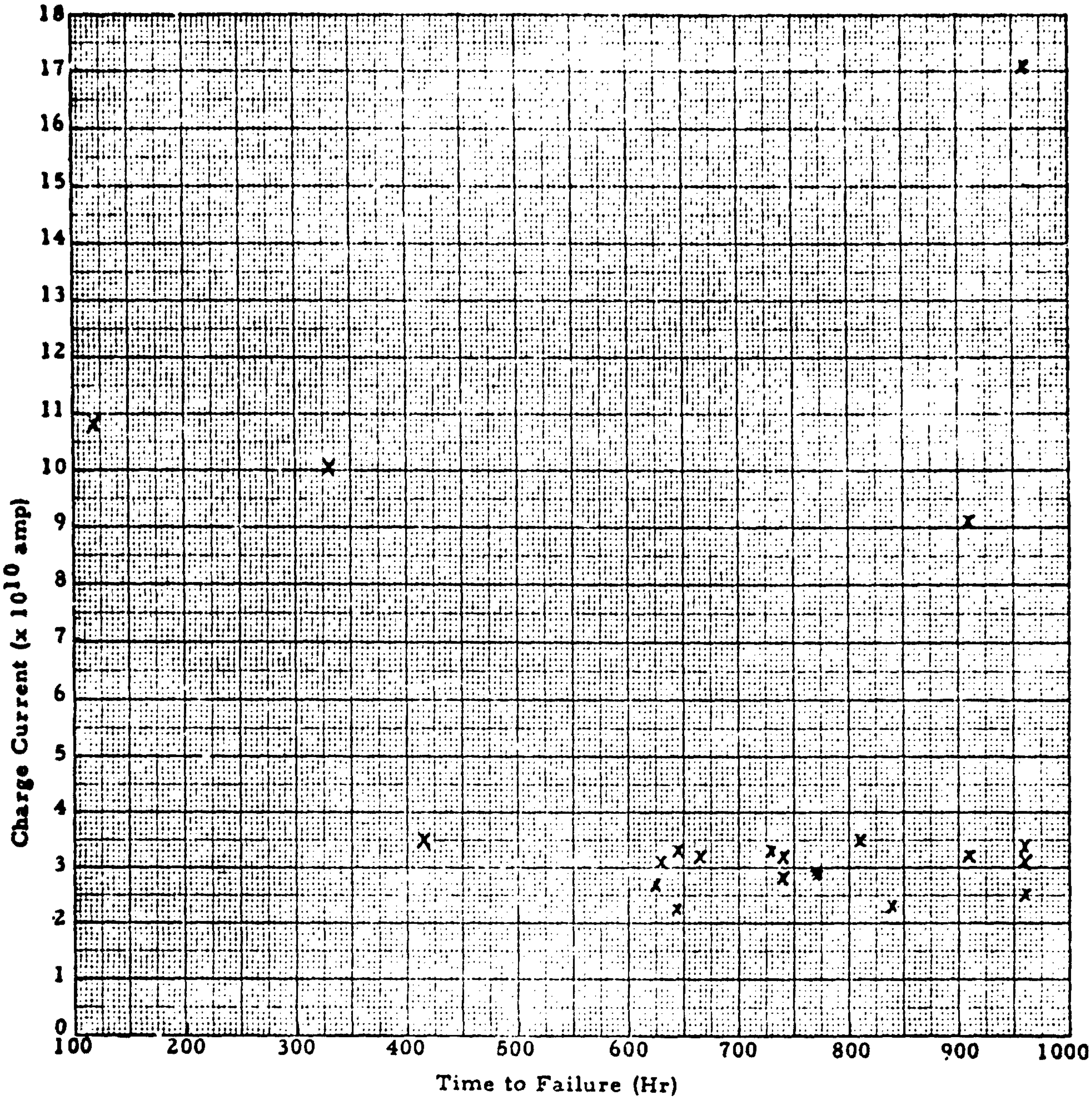


RELATIONSHIP BETWEEN CHARGE CURRENT AT 2 MIN
AND TIME TO FAILURE
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITORS (6000 μμF)

(Burn-in Conditions: 75 VDC/mil, 24 hr, 150°C;
Charge Conditions: 225 VDC, 150°C)

(Definition of Failure: electrical resistance < 20 MΩ)
(Dielectric Thickness: 0.0025 in.)

Figure 74

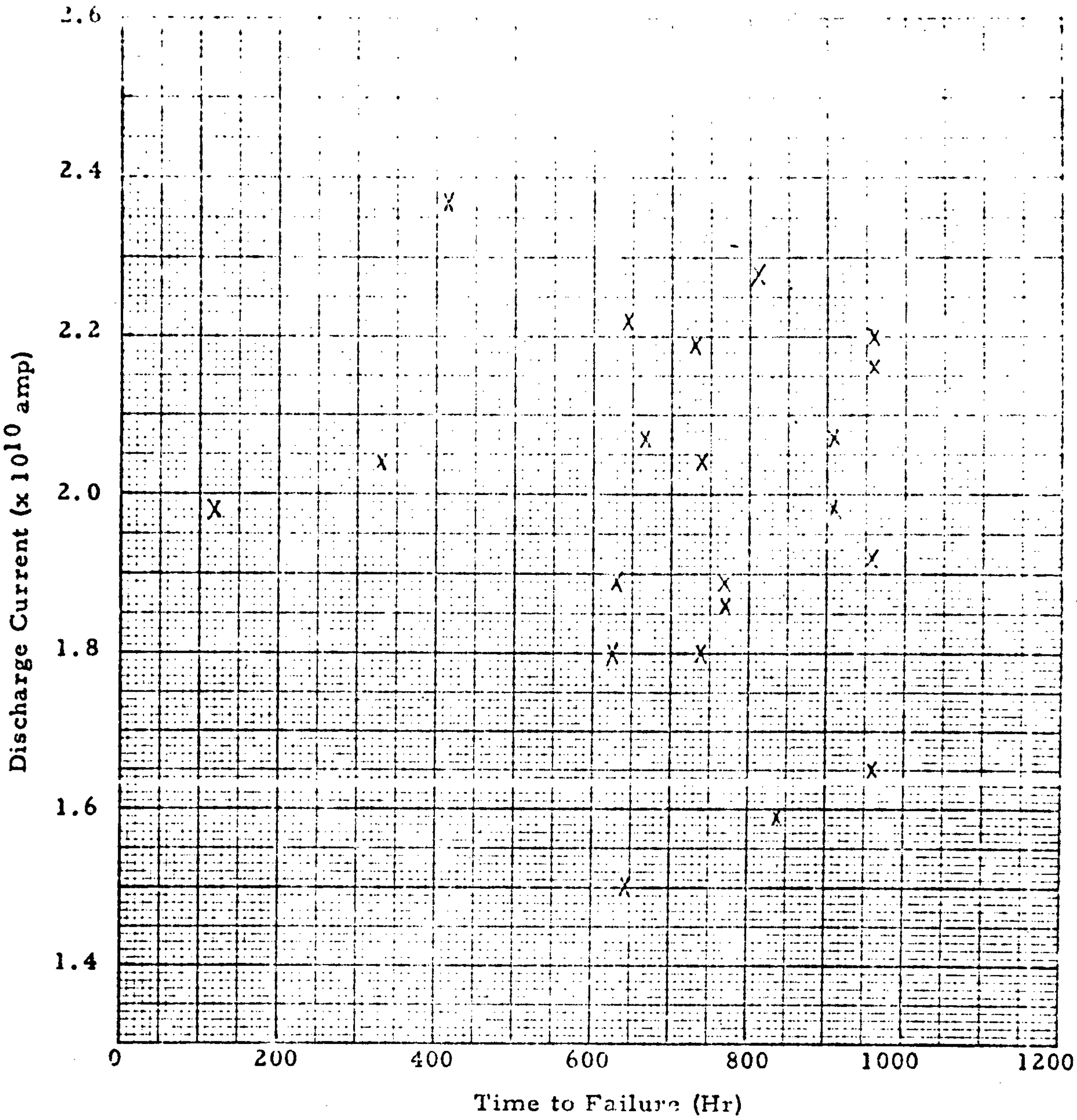


RELATIONSHIP BETWEEN CHARGE CURRENT AT 15 MIN
AND TIME TO FAILURE
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITORS (6000 $\mu\mu F$)

(Burn-in Conditions: 75 VDC/mil, 24 hr, 150°C;
Charge Conditions: 225 VDC, 150°C)

(Definition of Failure: electrical resistance < 20 MΩ)

Figure 75

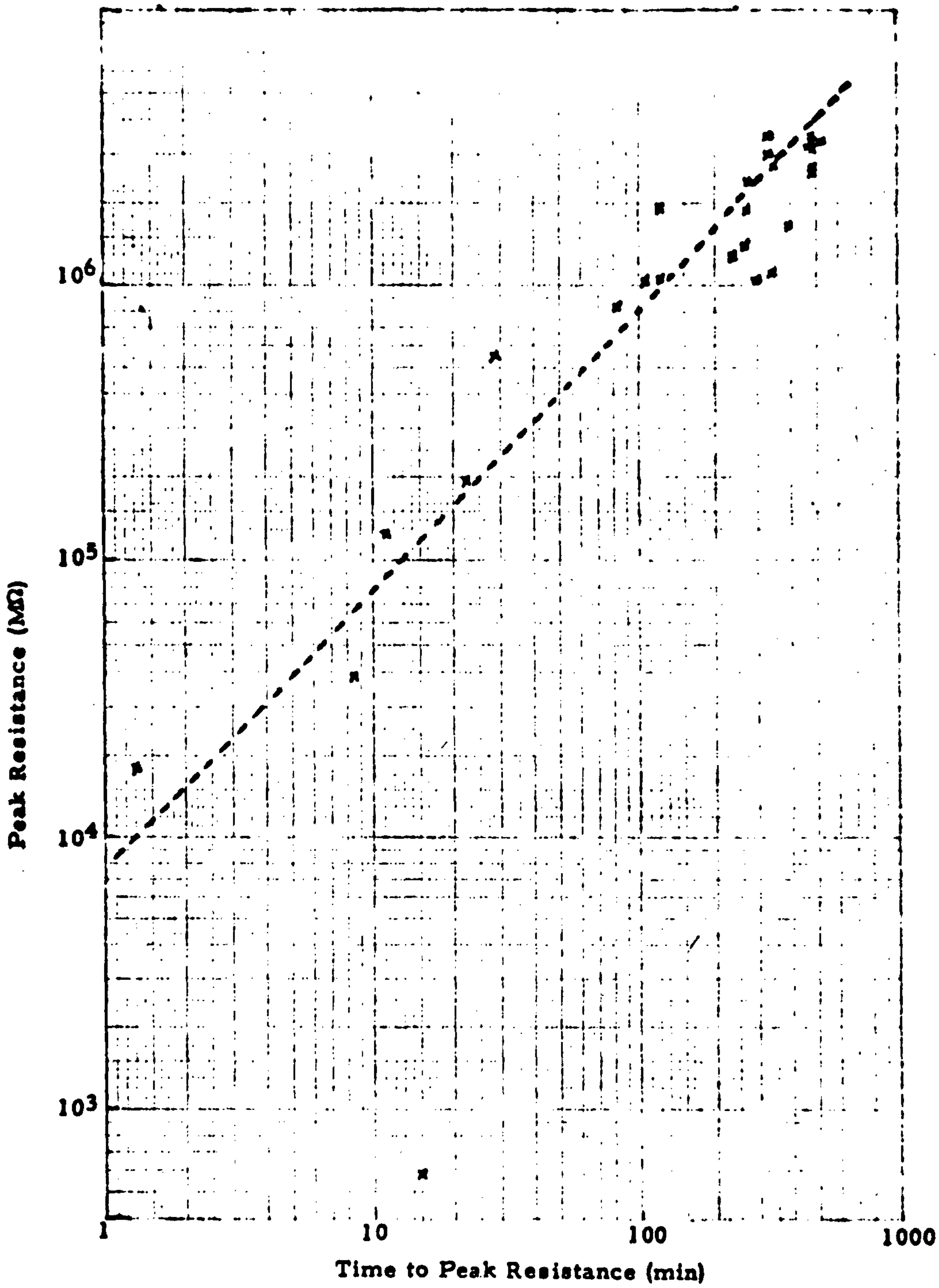


RELATIONSHIP BETWEEN DISCHARGE CURRENT AT 2 MIN
AND TIME TO FAILURE
FOR
C67 CASE SIZE I MONOLYTHIC CAPACITORS (6000 μμF)

(Burn-in Conditions: 75 VDC/mil, 24 hr, 150°C;
Charge Conditions: 225 VDC, 15 min, 150°C)

(Definition of Failure: electrical resistance < 20 MΩ)

Figure 76

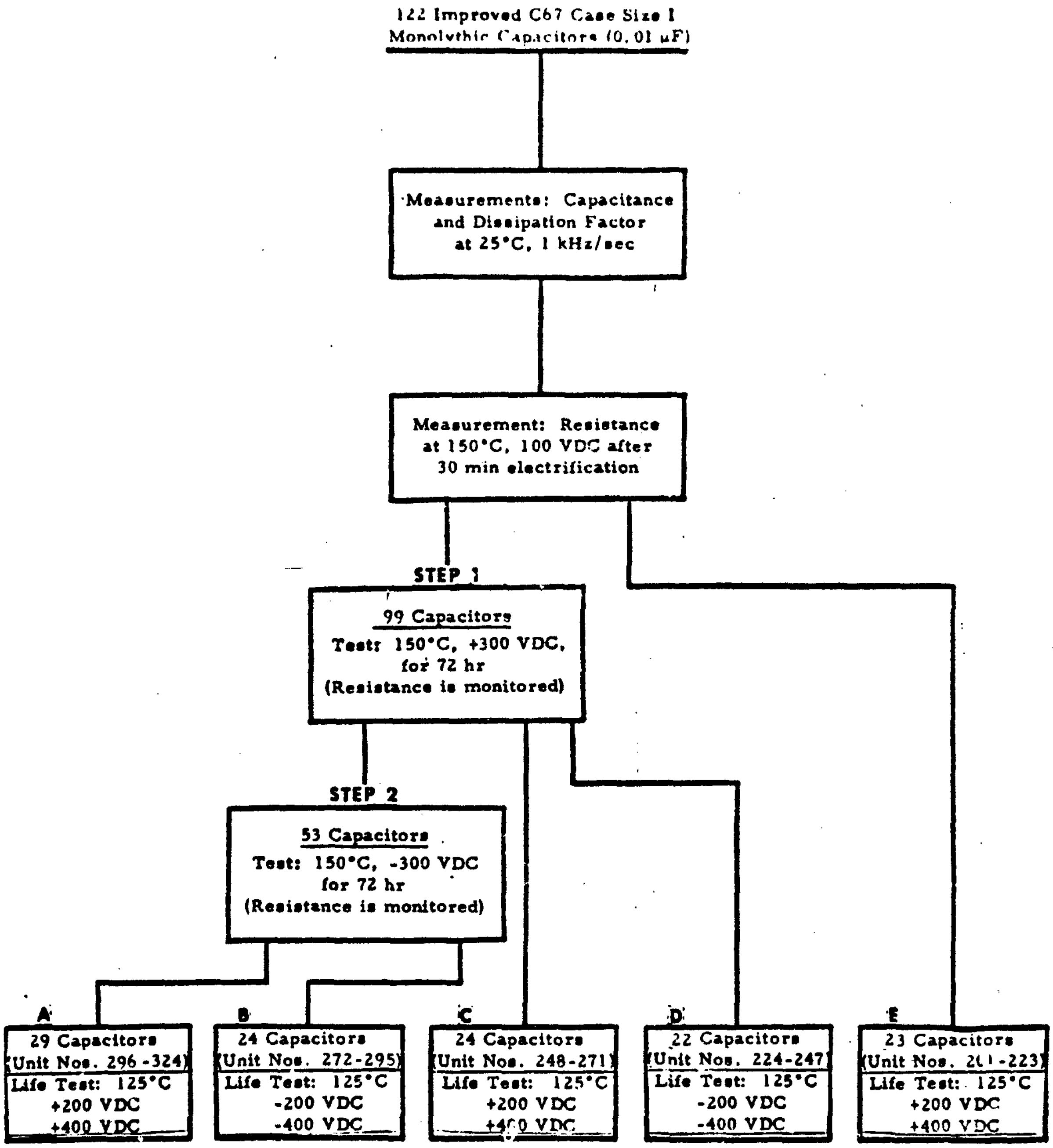


PEAK RESISTANCE VS TIME TO PEAK RESISTANCE FOR CASE SIZE I C67 MONOLYTHIC CAPACITORS

Charge Condition: 185 VDC, 150°C

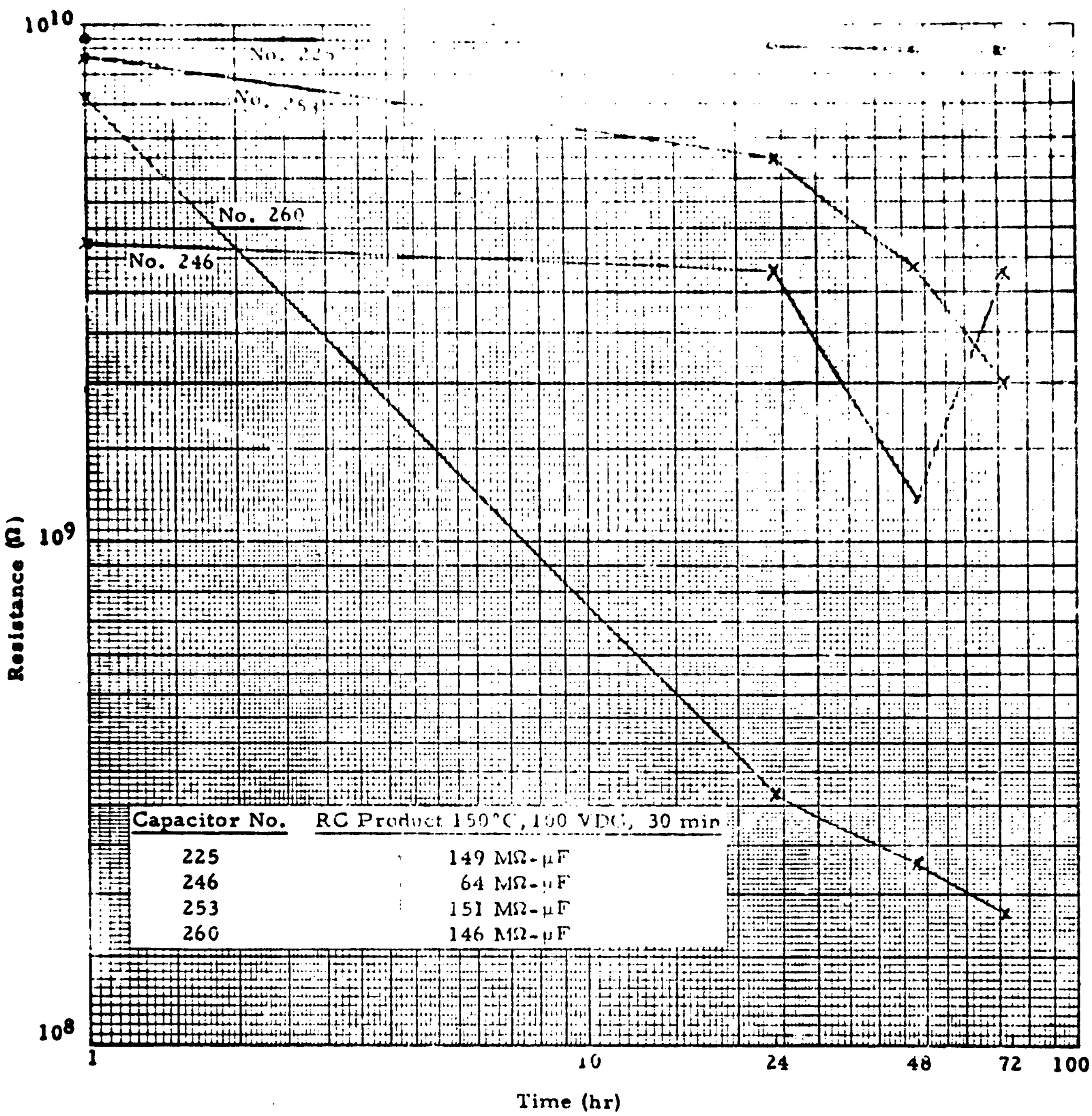
Dielectric Thickness: 0.0025 in.

Figure 77



EXPERIMENT TO SELECT CAPACITORS HAVING POTENTIALLY LONG LIVES

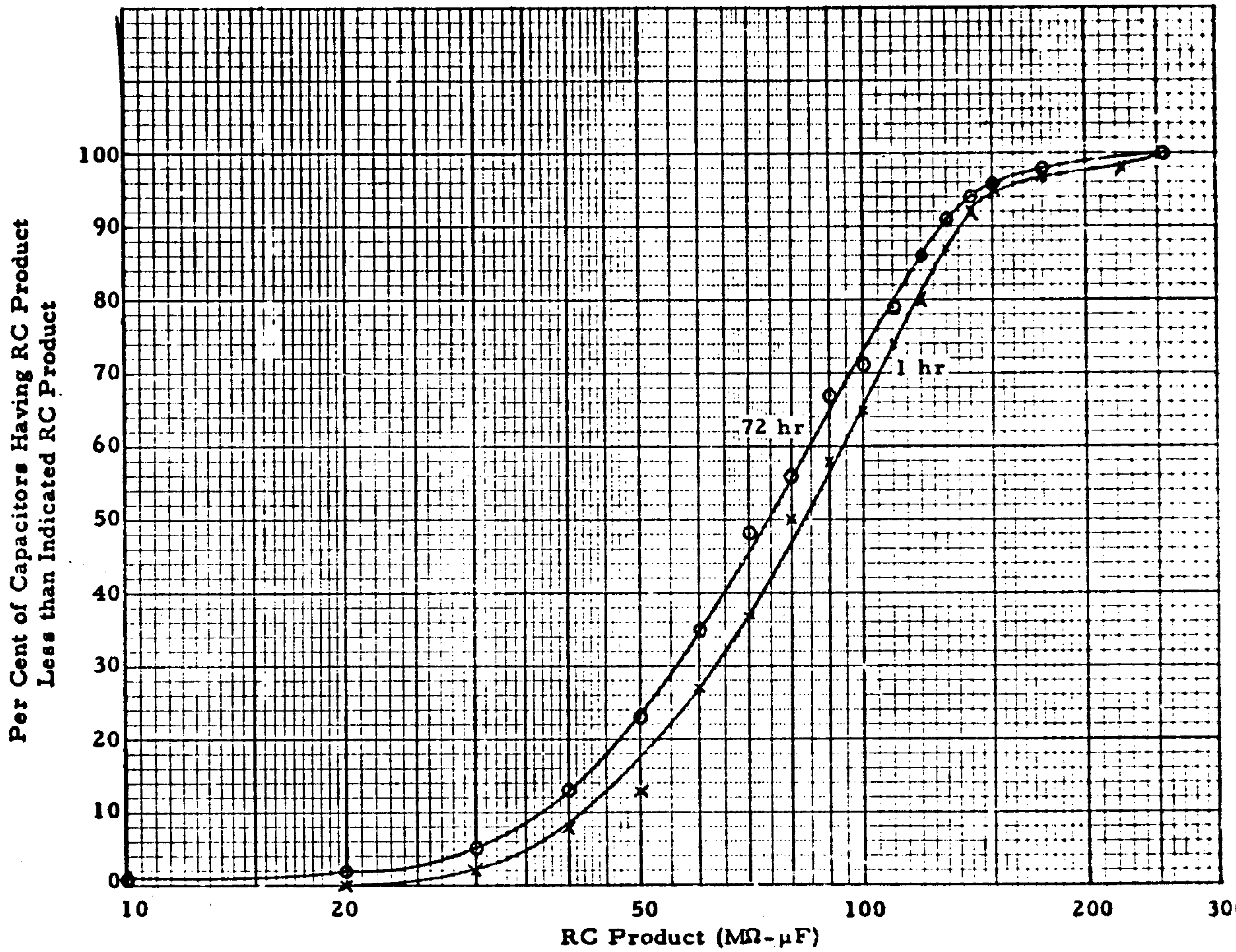
Figure 78



RESISTANCE VS TIME DURING INITIAL BURN-IN
FOR IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS

(Burn-In at 300 VDC, 150°C for 72 hr)

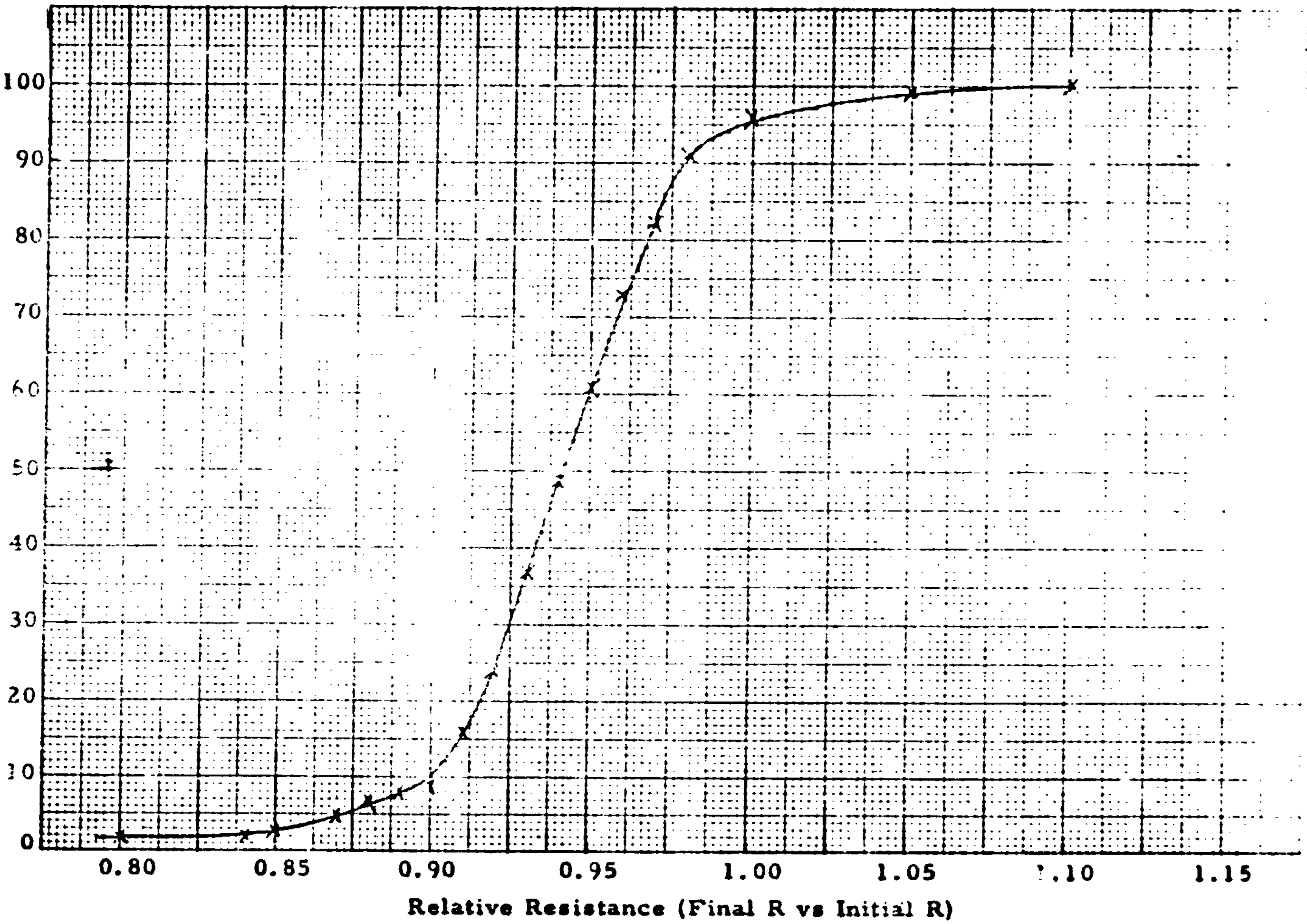
Figure 7c



DISTRIBUTION OF RC PRODUCTS DURING INITIAL BURN-IN AT 300 VDC, 150°C
FOR IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS

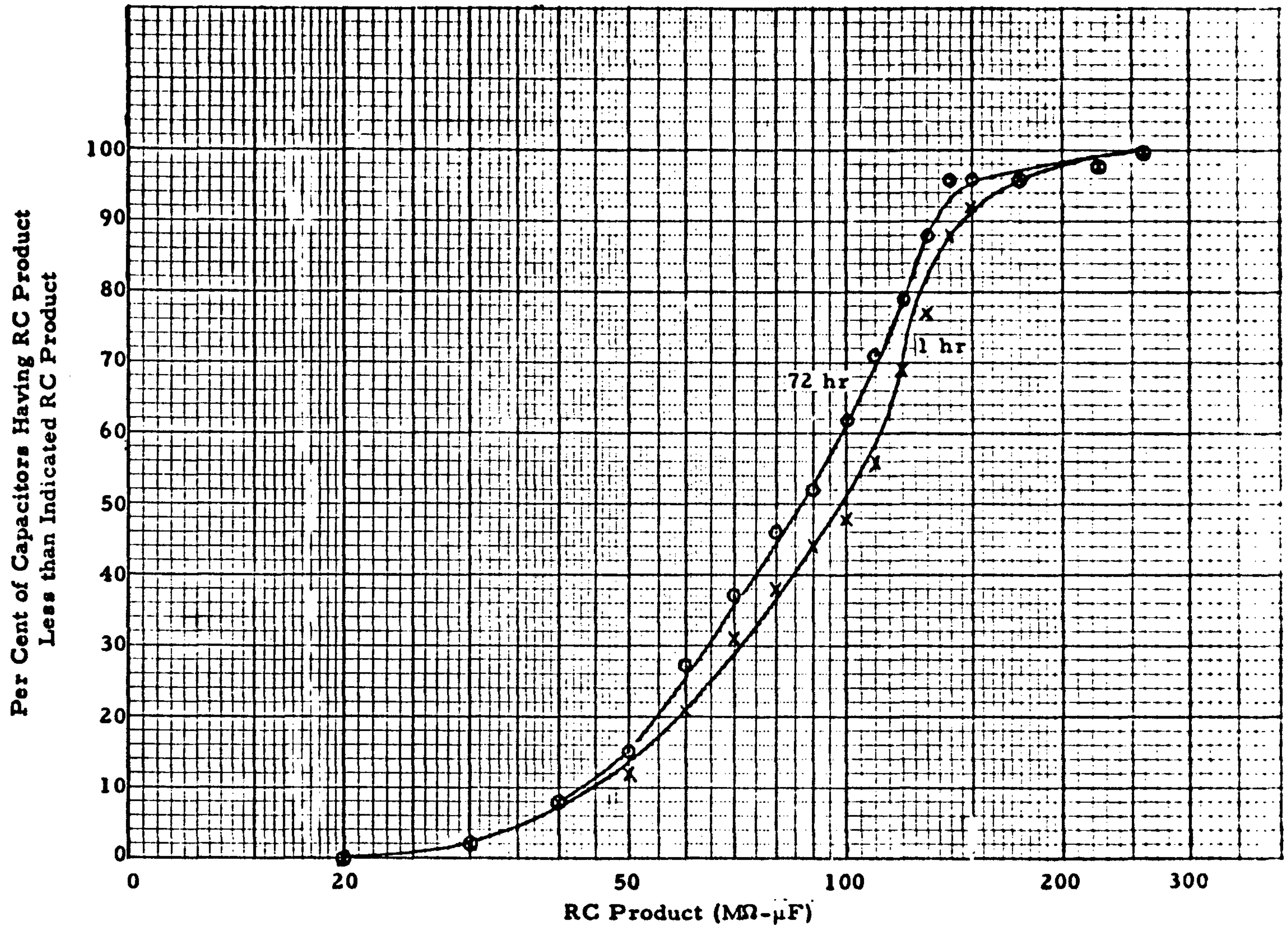
R at 300 VDC, 150°C
C at 0.5 V_{rms}, 25°C, 1 kHz

Figure 80



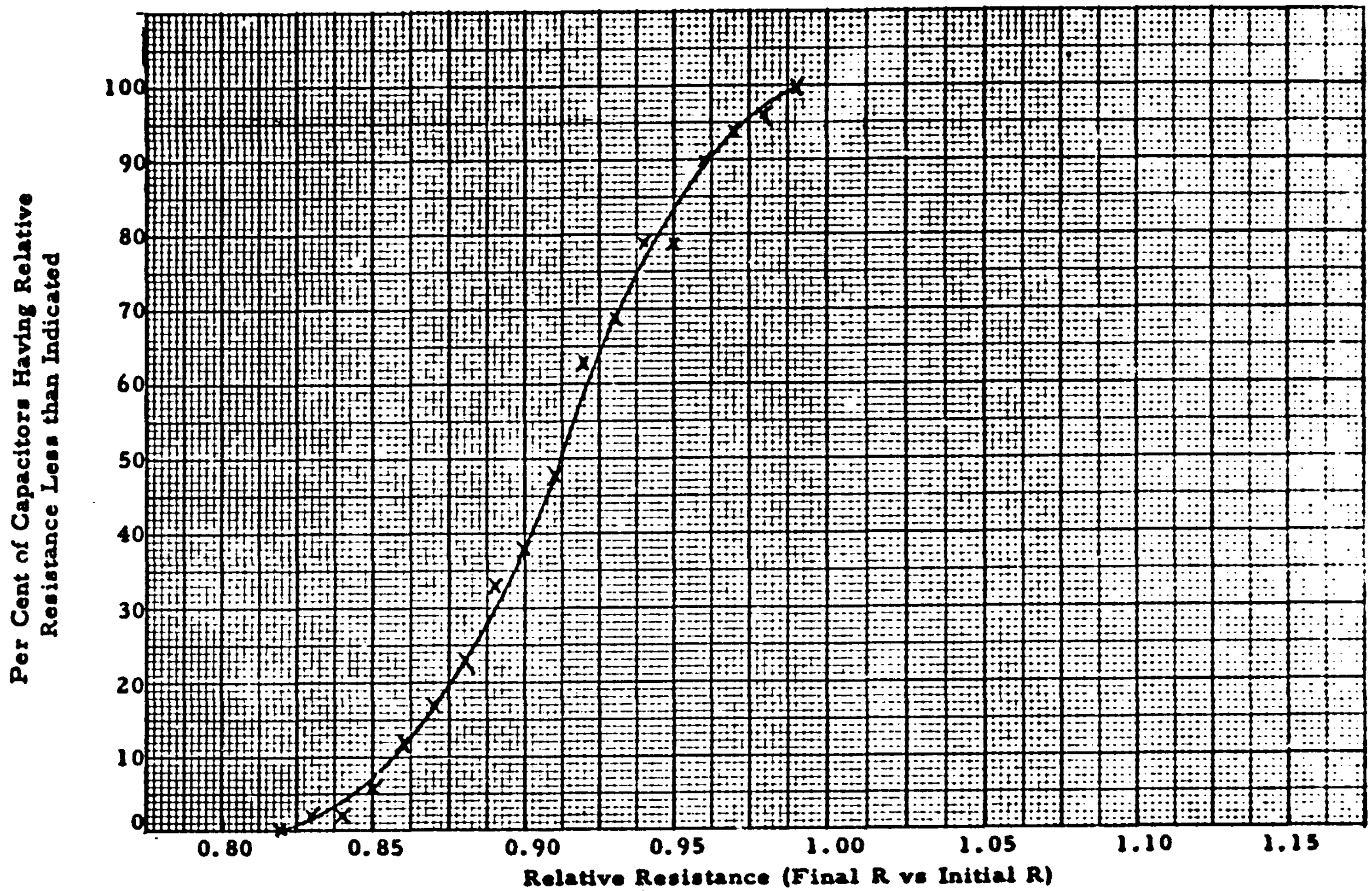
DISTRIBUTION OF RESISTANCE CHANGES DURING INITIAL BURN-IN FOR IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS
(Resistance at 72 hr burn-in relative to resistance after 1 hr burn-in)
(Burn-in Conditions: 150°C, 300 VDC, 72 hr)

Figure 8



DISTRIBUTION OF RC PRODUCTS DURING "REVERSE" BURN-IN
FOR IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS
R at 300 VDC, 150°C
C at 0.5 V_{rms}, 25°C, 1 kHz

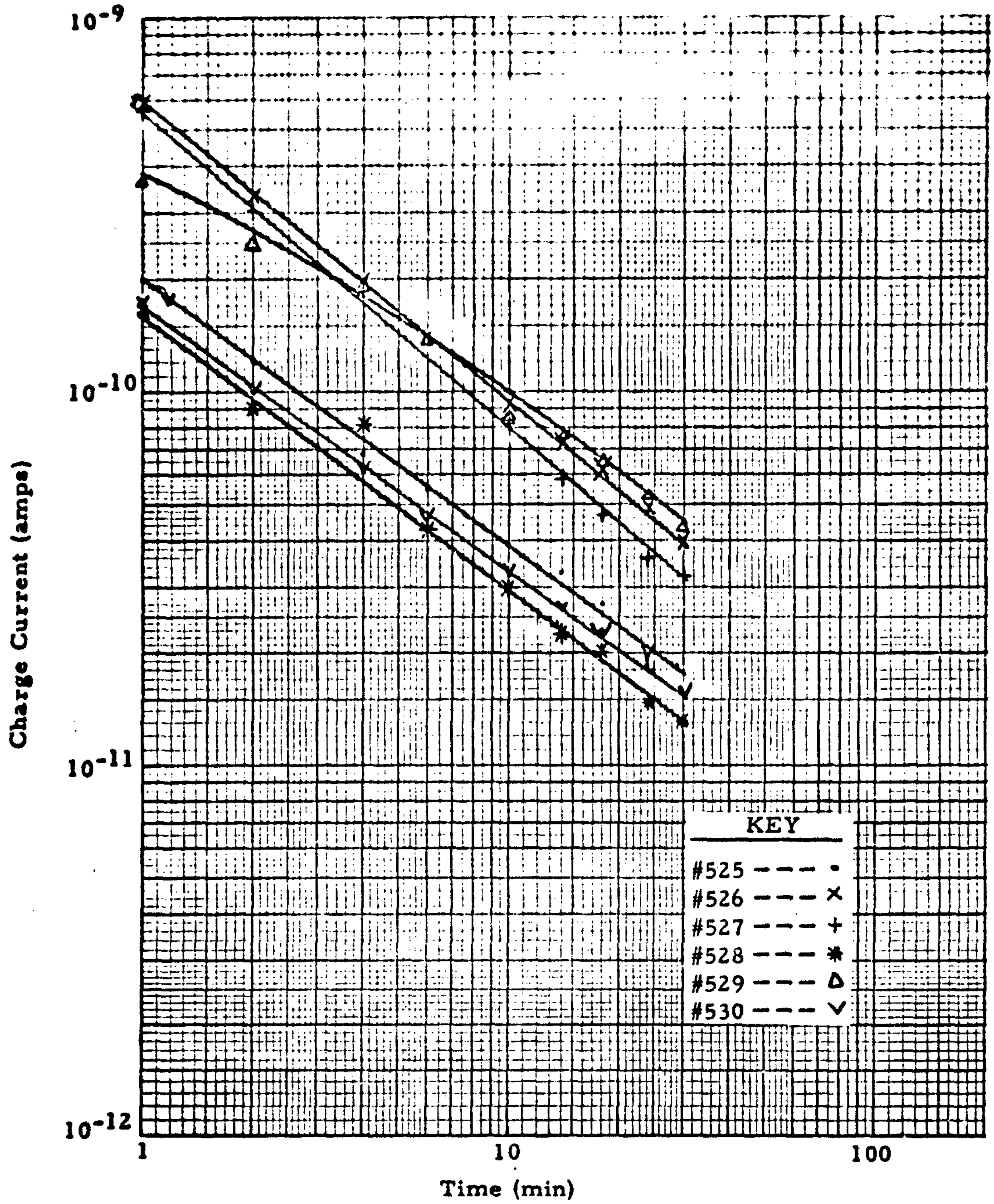
Figure 82



DISTRIBUTION OF RESISTANCE CHANGES DURING REVERSE BURN-IN FOR IMPROVED 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS

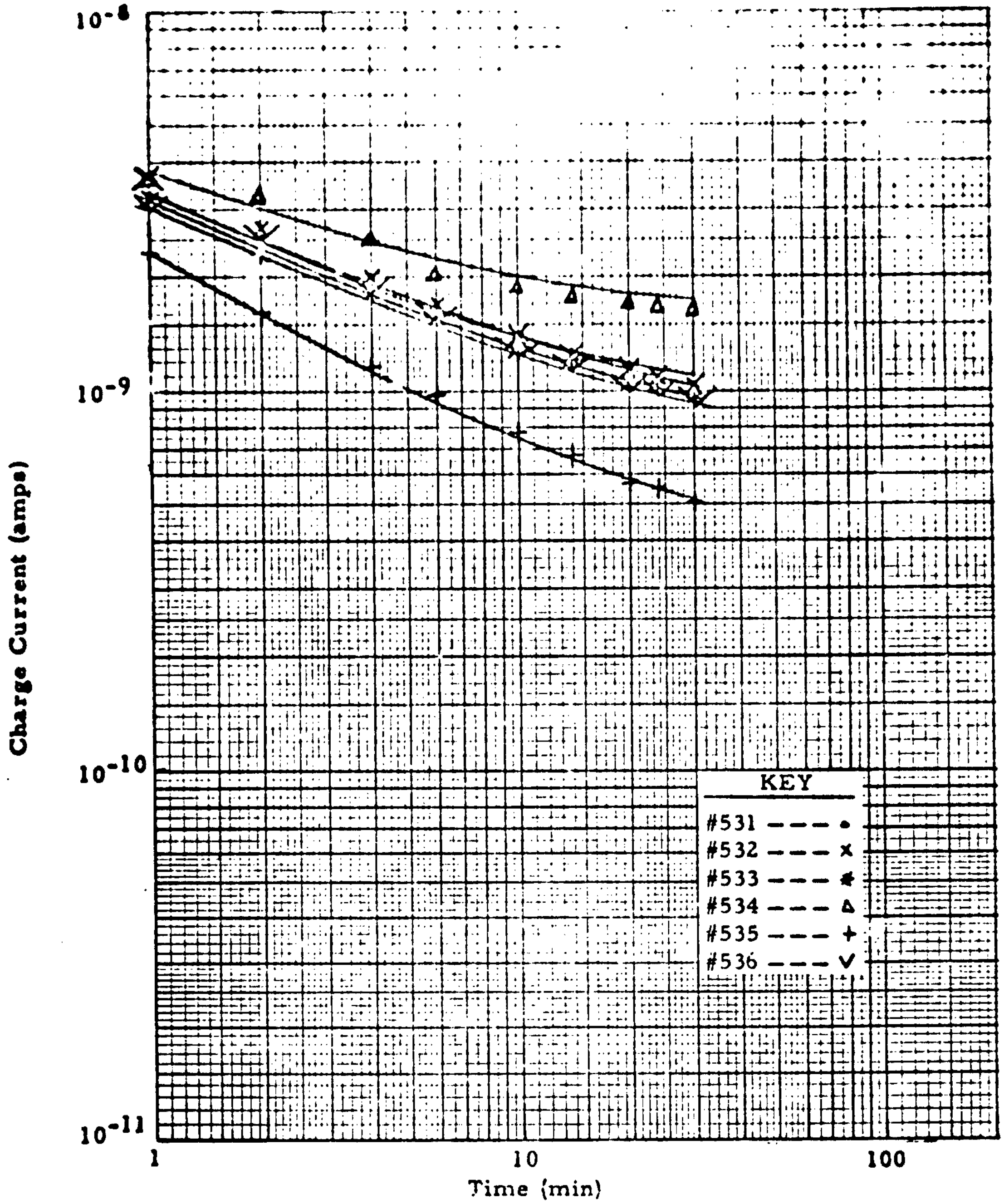
(Resistance at 72 hr burn-in relative to resistance after 1 hr burn-in)
(Burn-in Conditions: 150°C, 300 VDC, 72 hr)

Figure 83



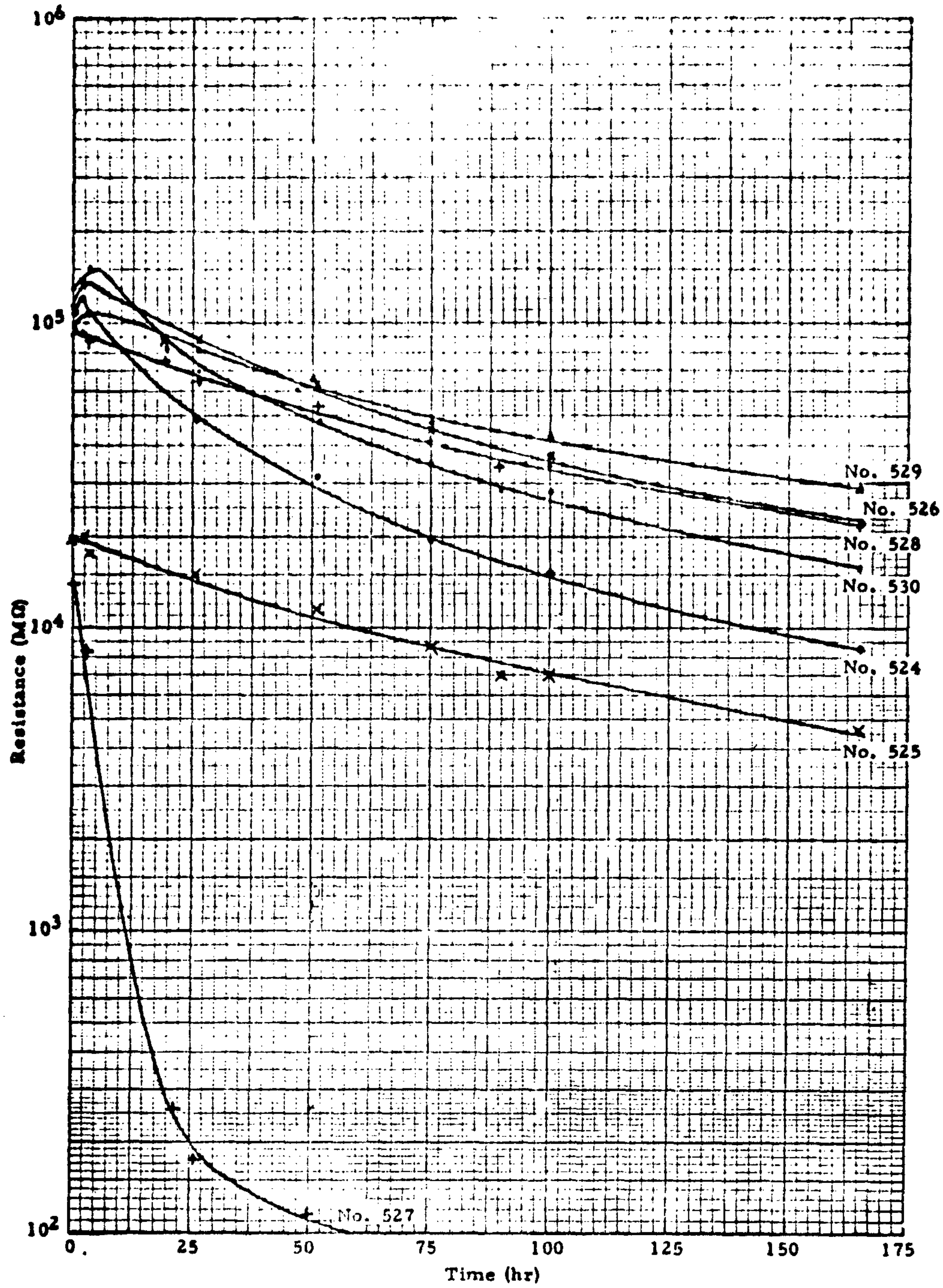
CHARGE CURRENT VS TIME AT 195 VDC, 25°C
FOR IMPROVED 0.01 μF CASE SIZE I C67 MONOLYTHIC CAPACITORS (Lot 6S9205)

Figure 84



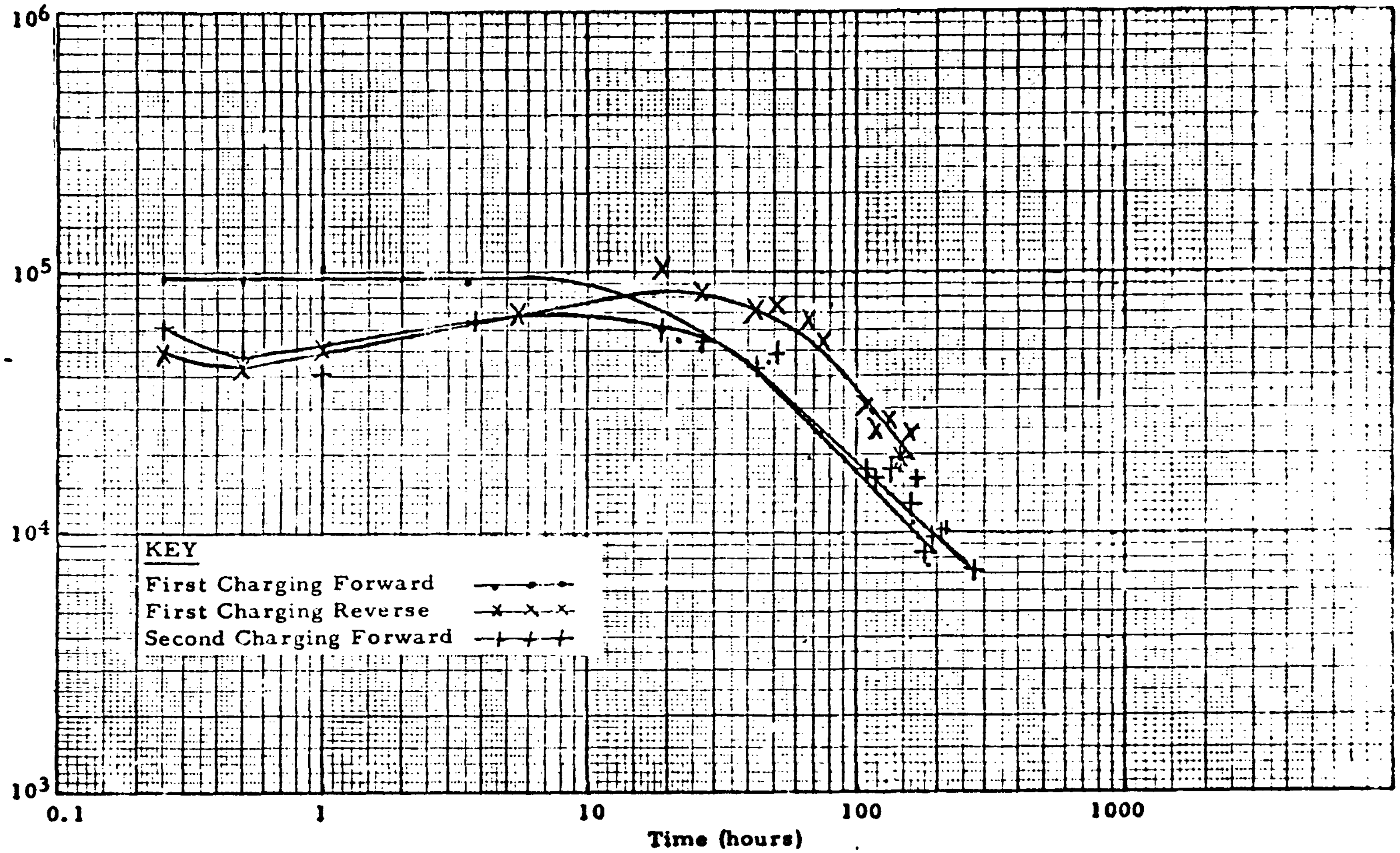
CHARGE CURRENT VS TIME AT 195 VDC, 150°C
FOR IMPROVED 0.01 μF CASE SIZE I C67 MONOLYTHIC CAPACITORS (Lot 6S9205)

Figure 85



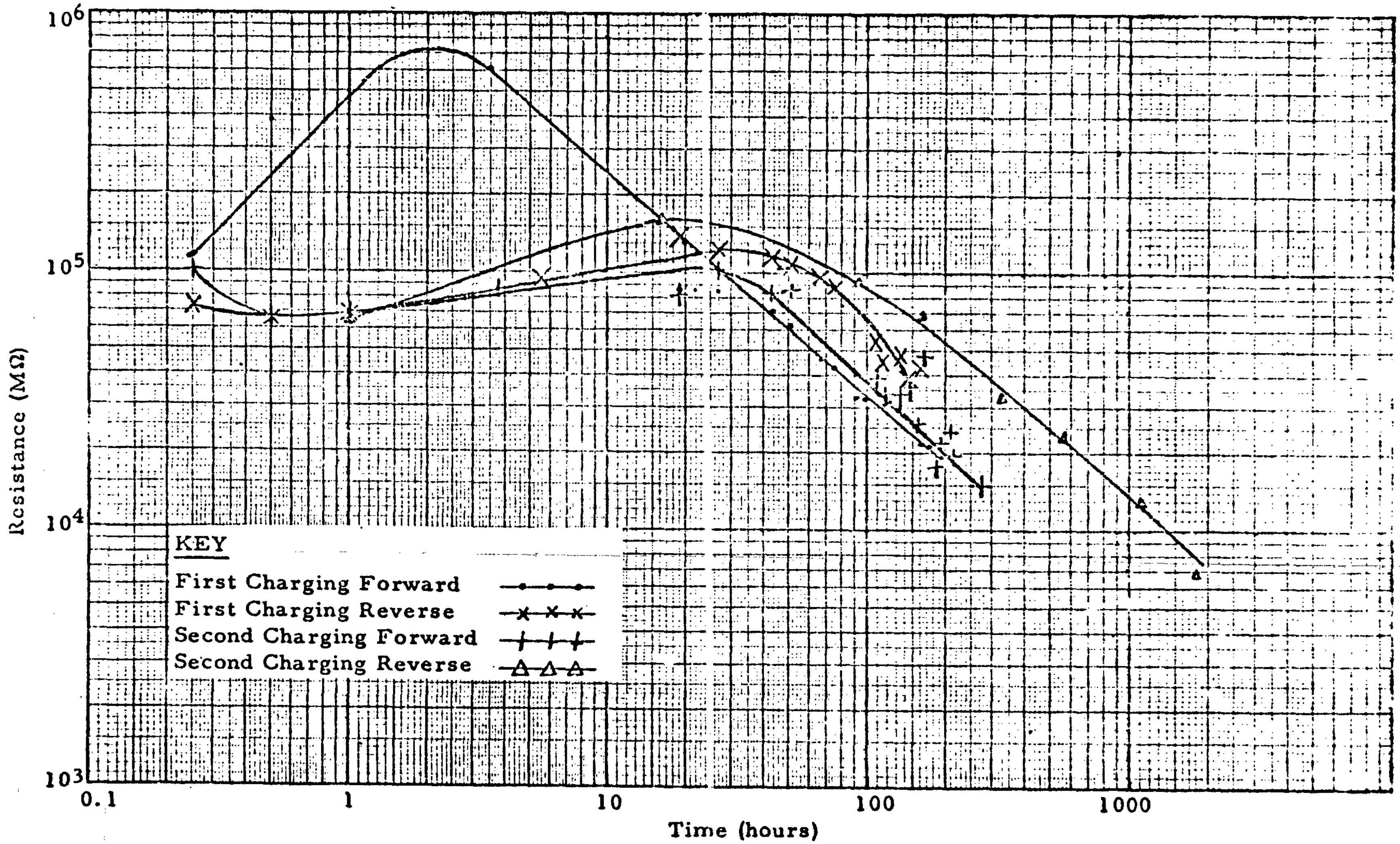
RESISTANCE VS TIME AT 195 VDC, 150°C
FOR 0.01 μF CASE SIZE I C67 MONOLYTHIC CAPACITORS (Lot 6S9205)

Figure 86



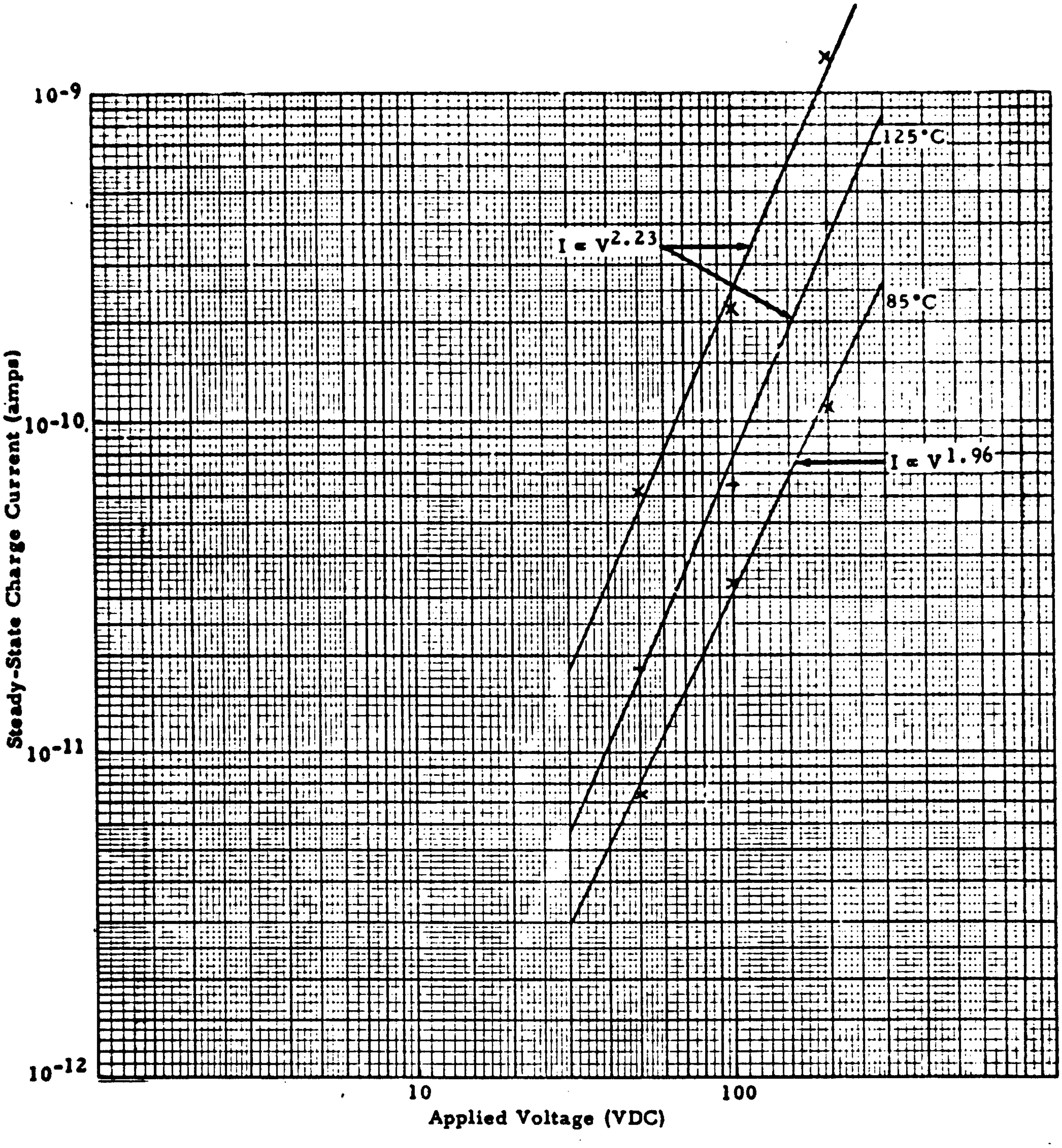
RESISTANCE VS TIME AT 195 VDC, 150°C
FOR A 0.01 μF CASE SIZE I C67 MONOLYTHIC CAPACITOR (Lot 6S9205, No. 30841)

Figure 87



RESISTANCE VS TIME AT 195 VDC, 150°C
FOR A 0.01 μF CASE SIZE I C67 MONOLYTHIC CAPACITOR (Lot 6S9205, No. 30836)

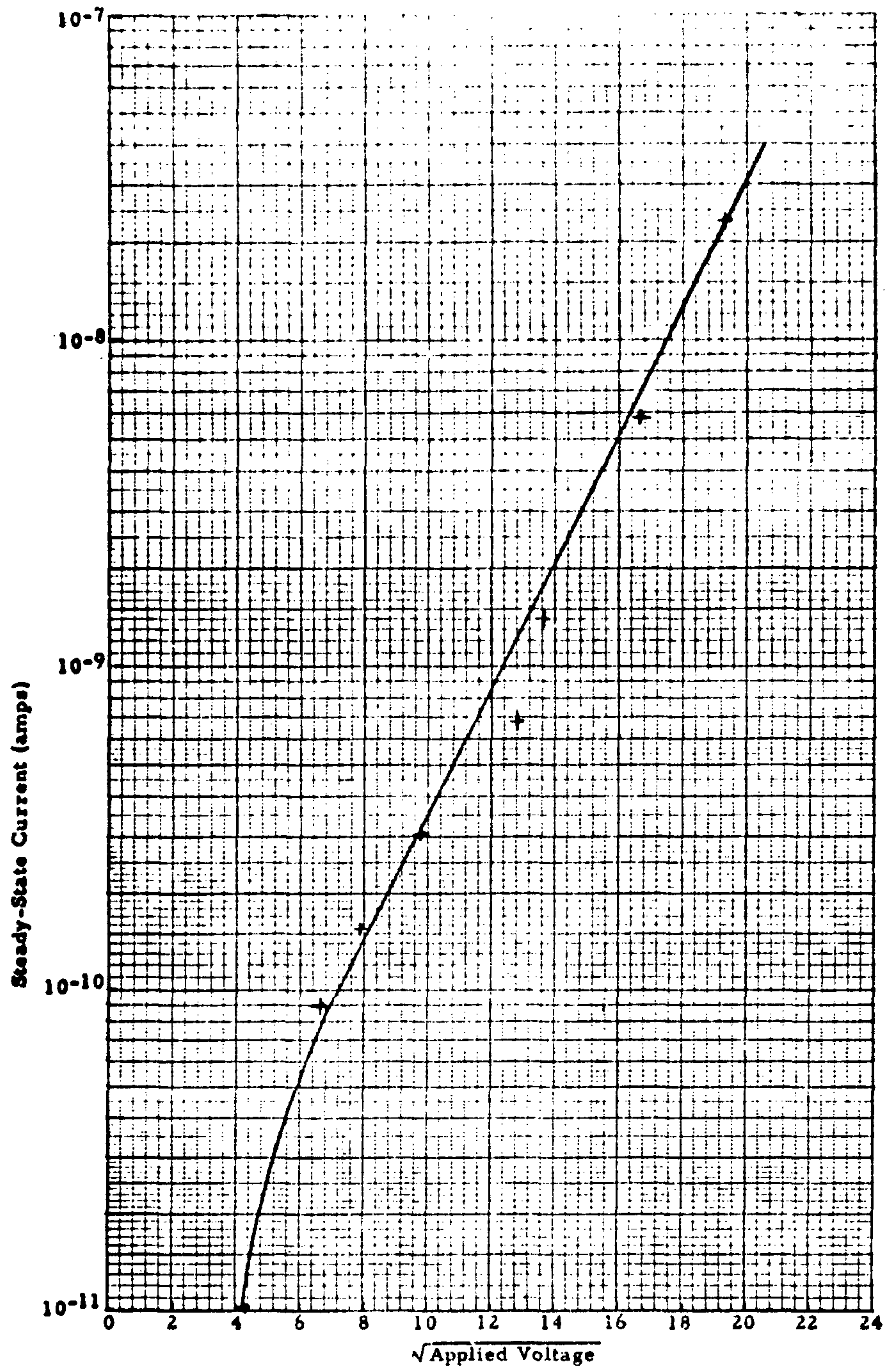
Figure 88



STEADY-STATE CHARGE CURRENTS VS APPLIED VOLTAGE AT 85°C, 125°C, AND 150°C

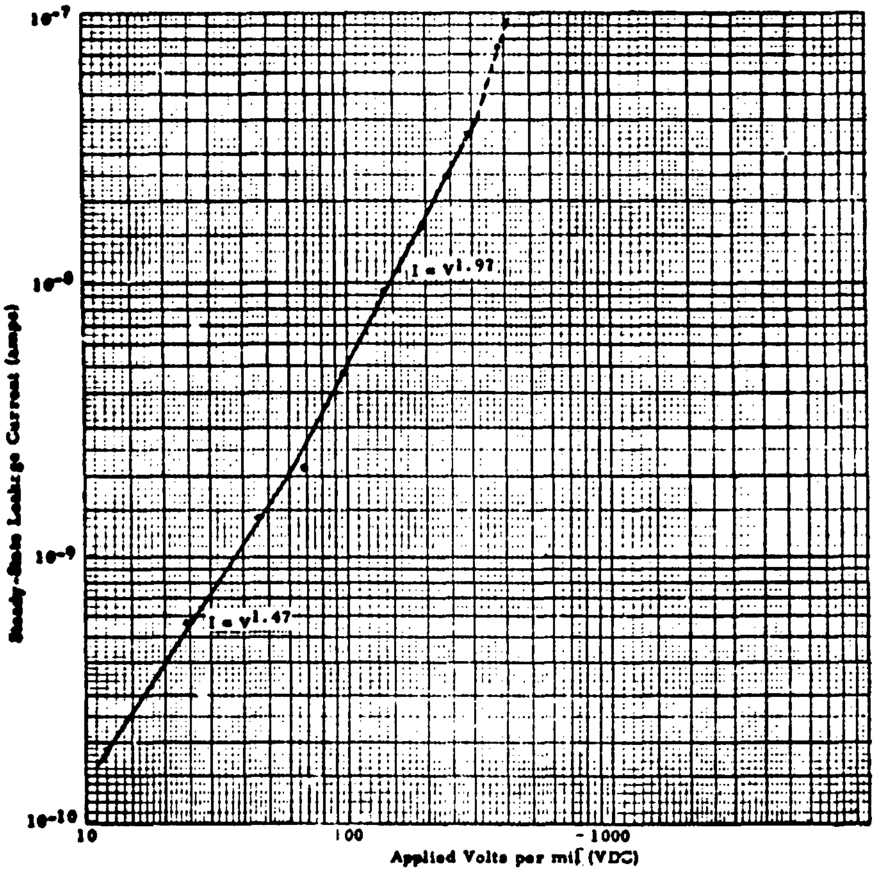
[Each point is the average value of 10 improved 0.01 μF C67 Case Size I MONOLYTHIC capacitors (Lot 6S9205)]

Figure 89



STEADY-STATE CURRENT VS SQUARE ROOT OF APPLIED VOLTAGE AT 150°C FOR A LOT 6S9205 CAPACITOR

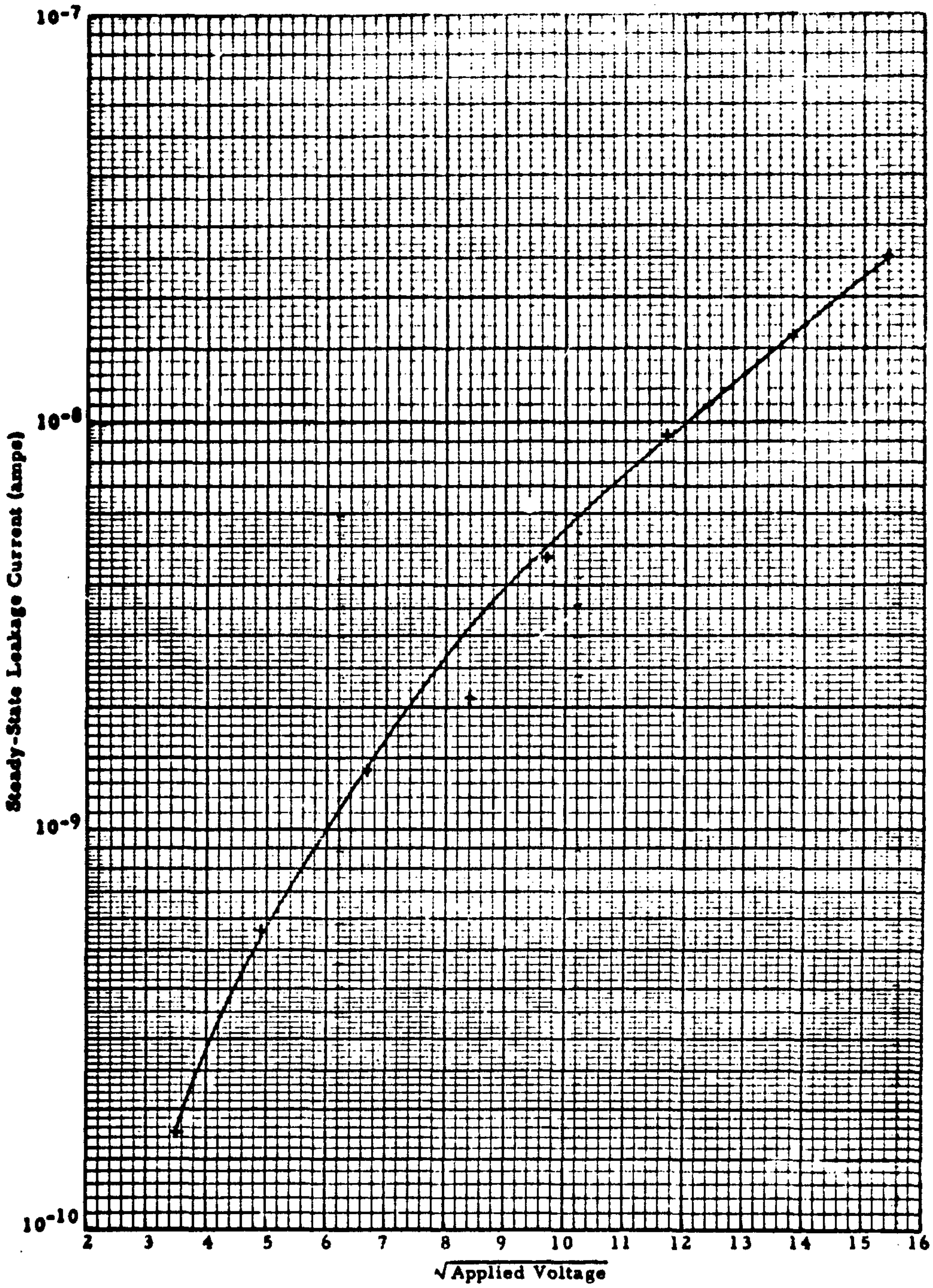
Figure 90



STEADY-STATE LEAKAGE CURRENT VS APPLIED VOLTAGE AT 150°C FOR A LOT 6511446 CAPACITOR

(C67 Ceramic, 0.001 in. dielectric layers, Case Size I MONOLYTHIC, 0.037 µF, Unit No. 1008, Pre-production sampling)

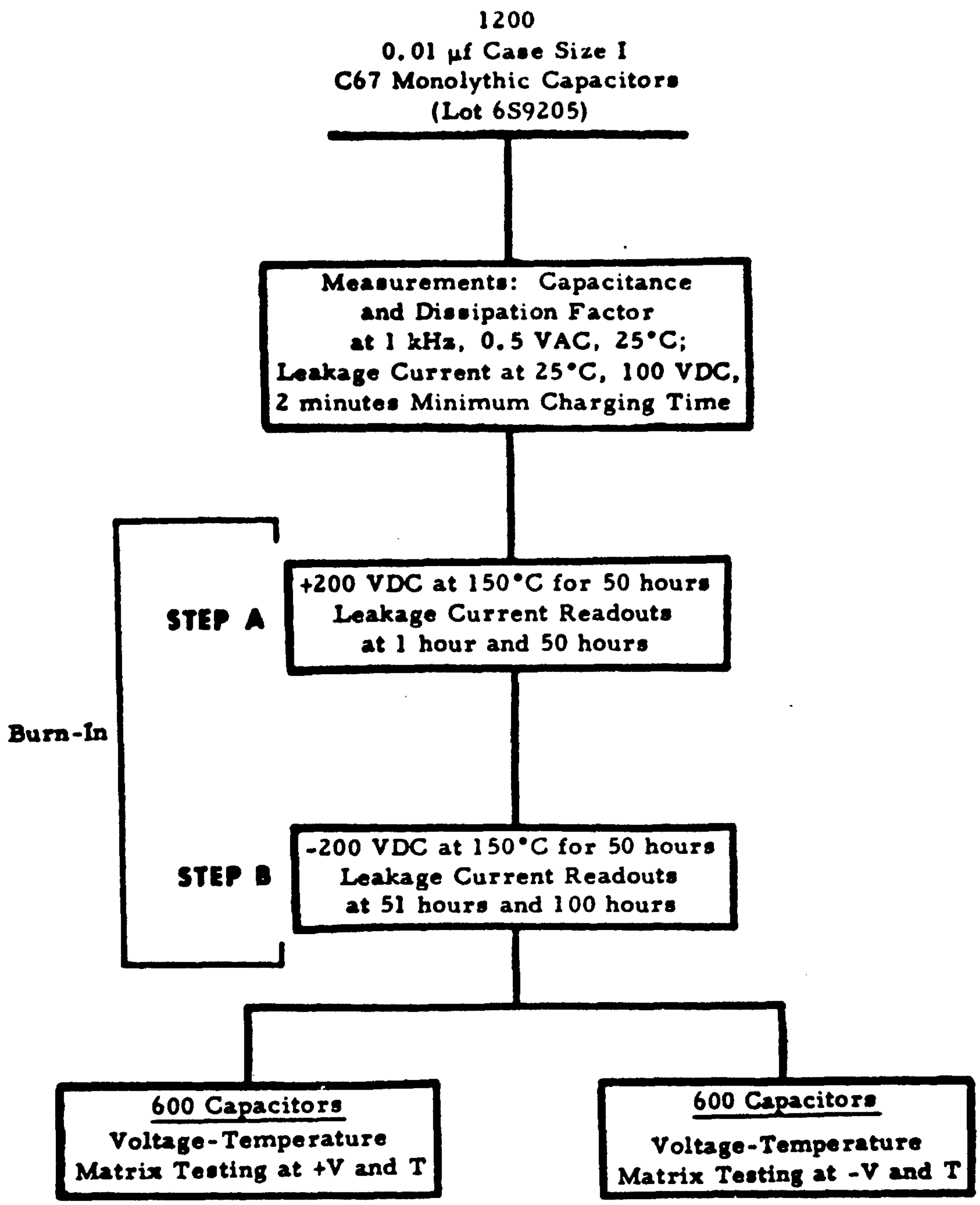
Figure 91



STEADY-STATE LEAKAGE CURRENT VS SQUARE ROOT OF APPLIED VOLTAGE AT 150°C FOR A LOT 6511446 CAPACITOR

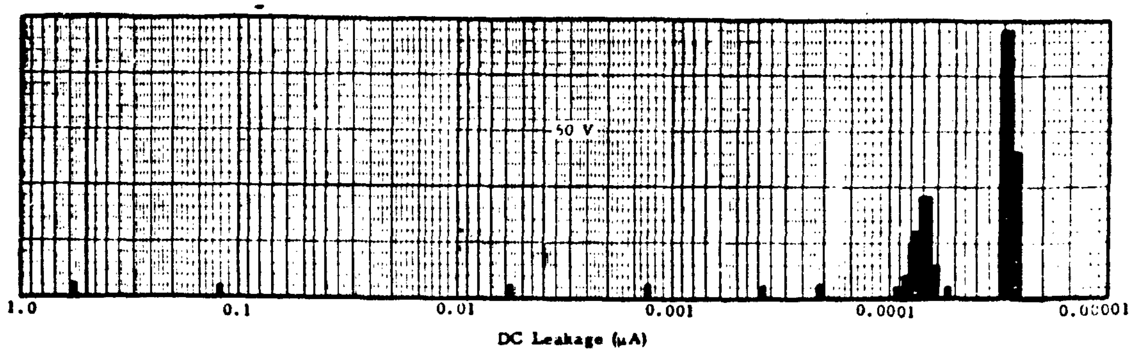
(C67 Ceramic, 0.001 in. dielectric layers, Case Size I MONOLYTHIC, 0.037 uF, Unit No. 1008, Pre-production sampling)

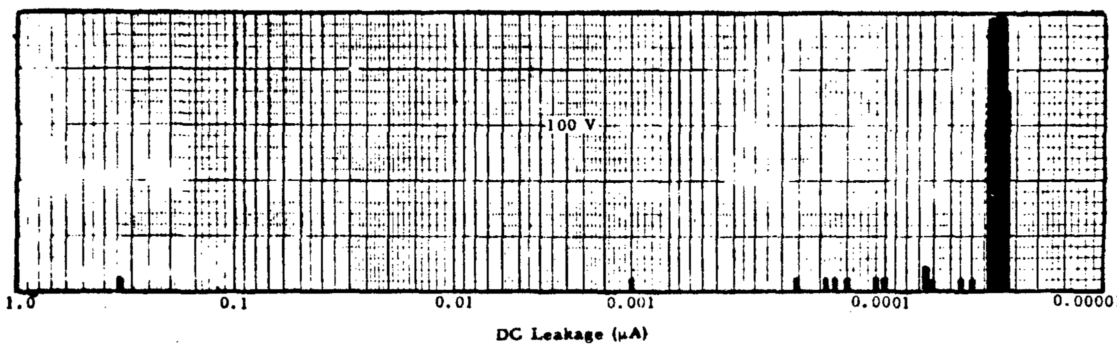
Figure 92

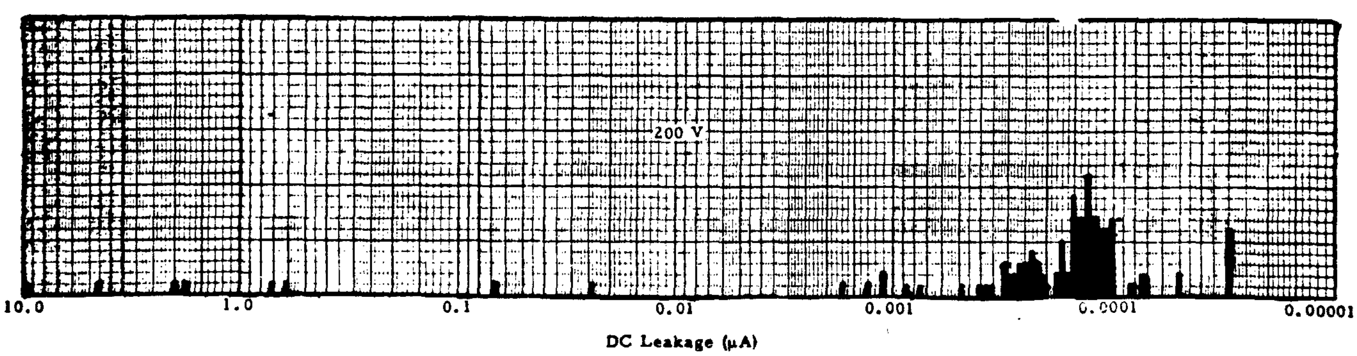


OUTLINE OF FIRST LIFE TEST MATRIX
FOR 0.01 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS

Figure 93

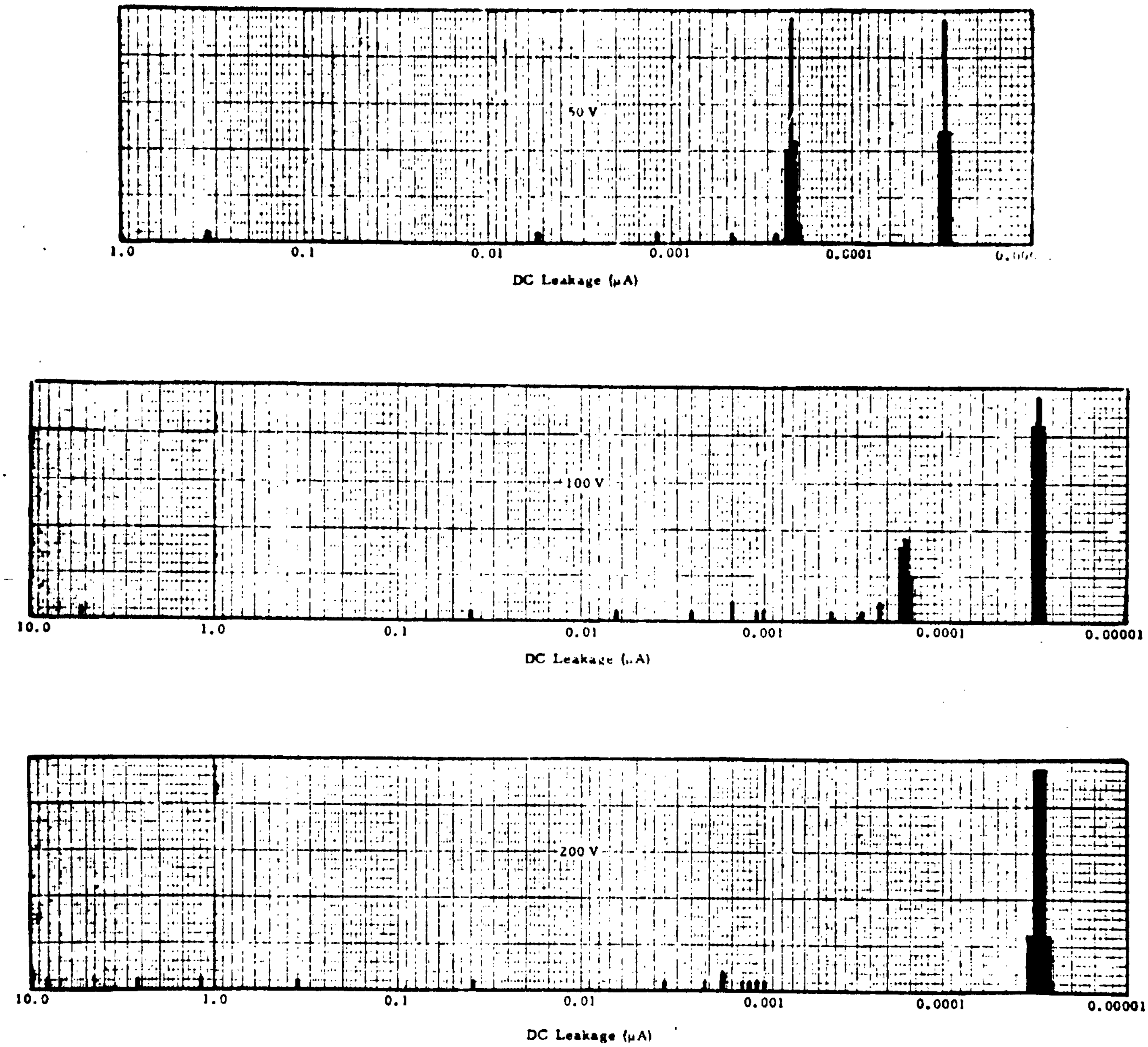






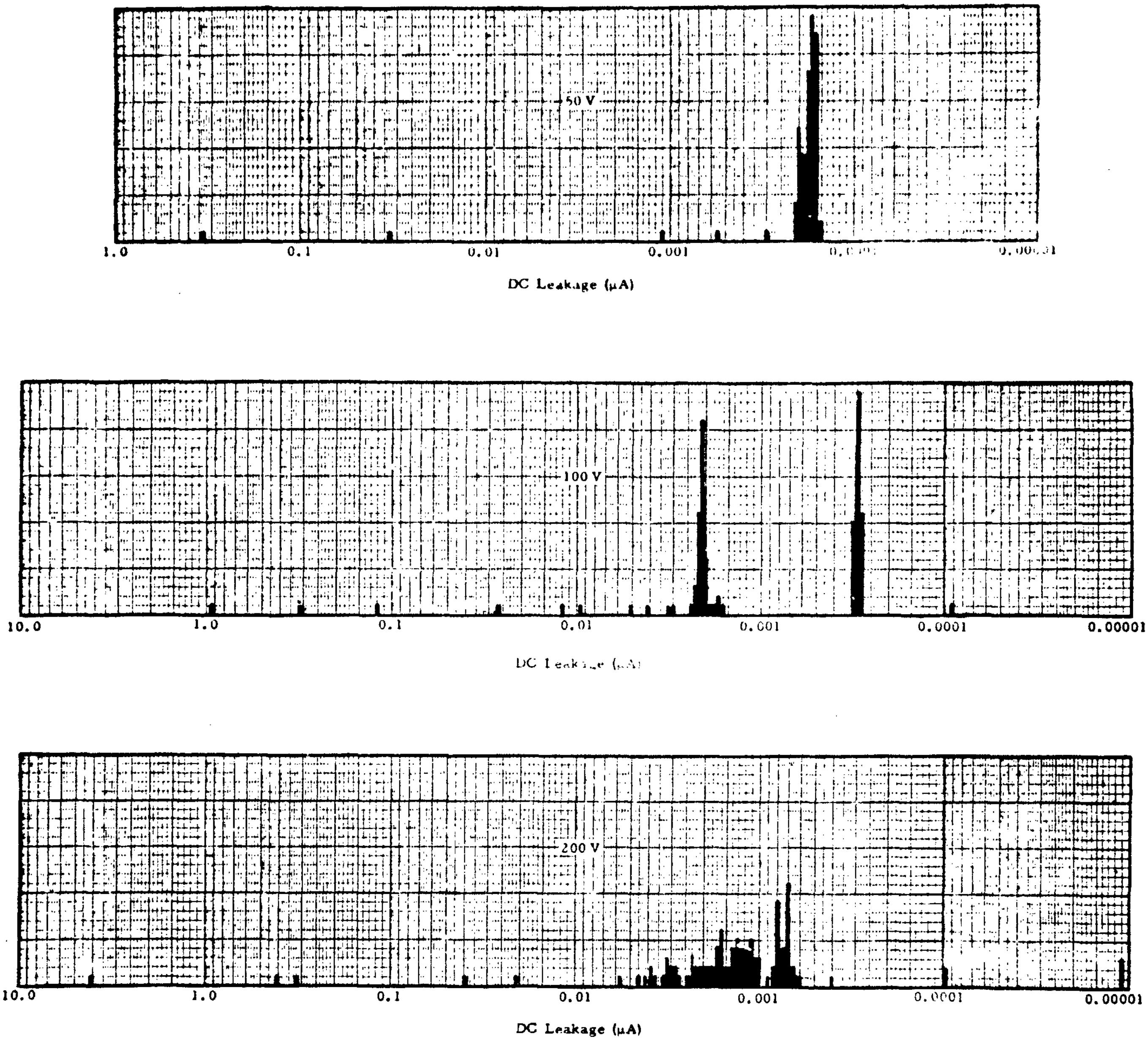
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 85°C 10,000 HOUR LIFE TEST
FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 6S92U5)

Figure 94



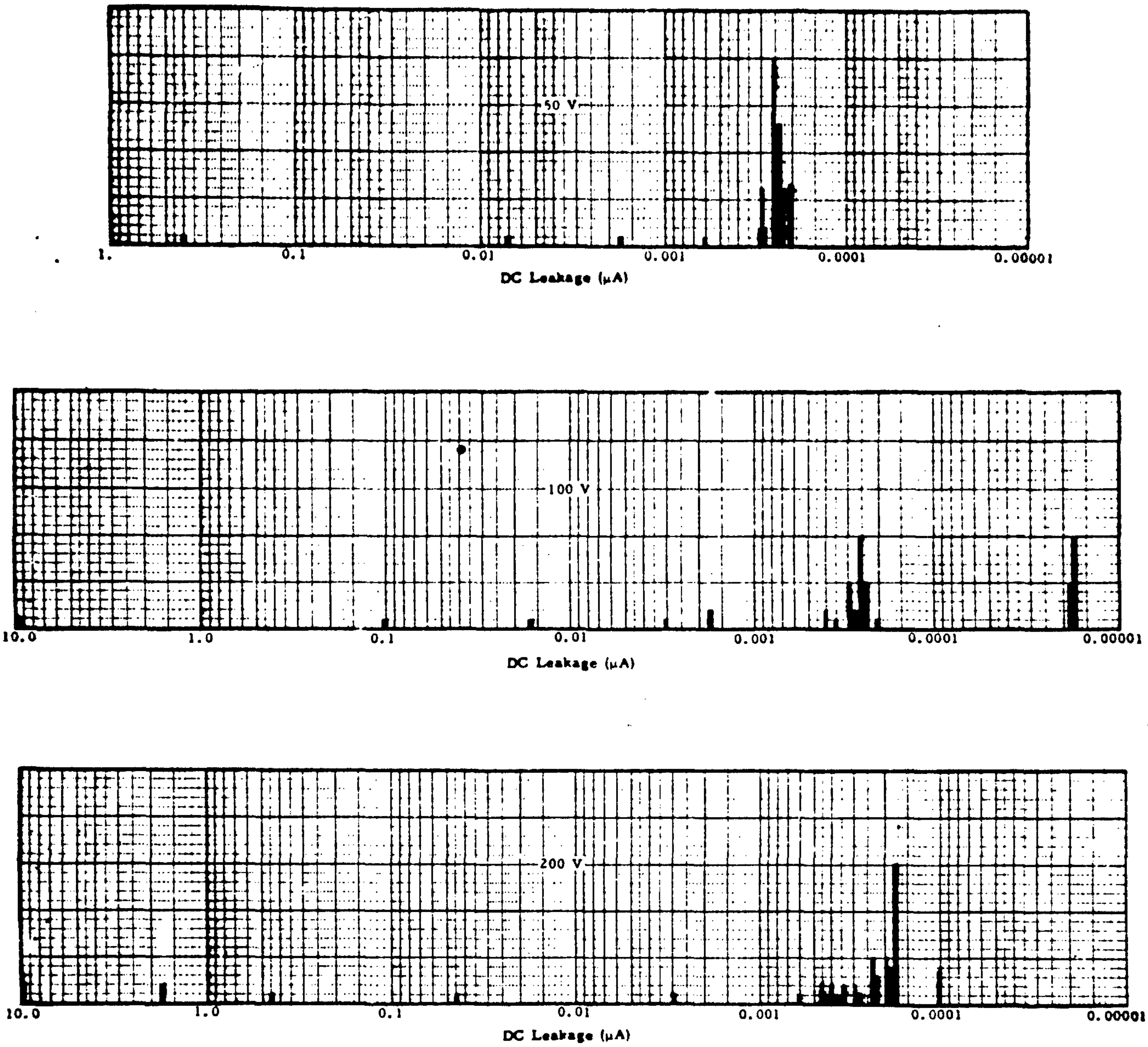
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 85°C 15,000 HOUR LIFE TEST
FOR 0.01 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 6S9205)

Figure 95



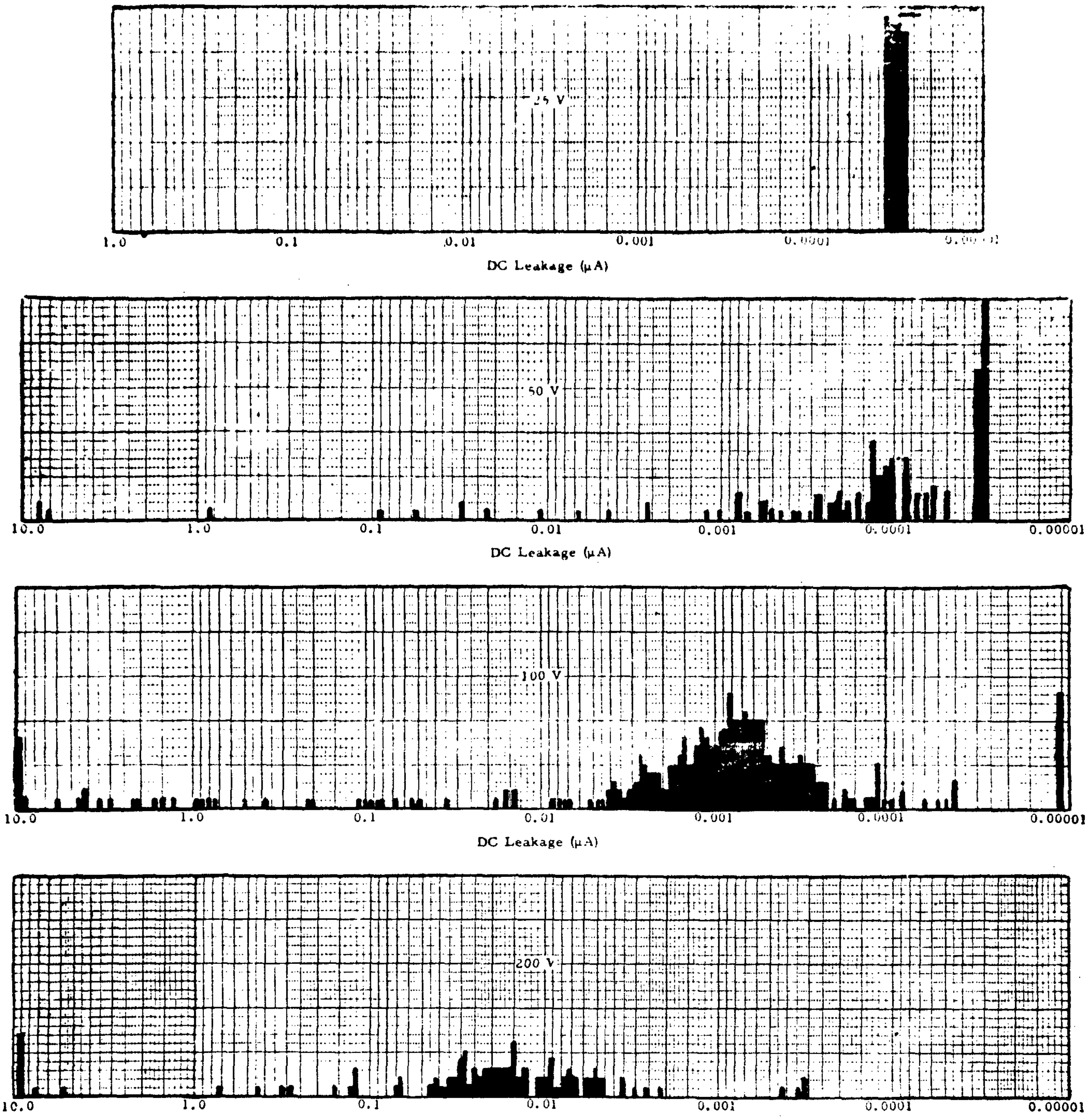
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 85°C 20,000 HOUR LIFE TEST
FOR 0.01 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 6S9205)

Figure 96



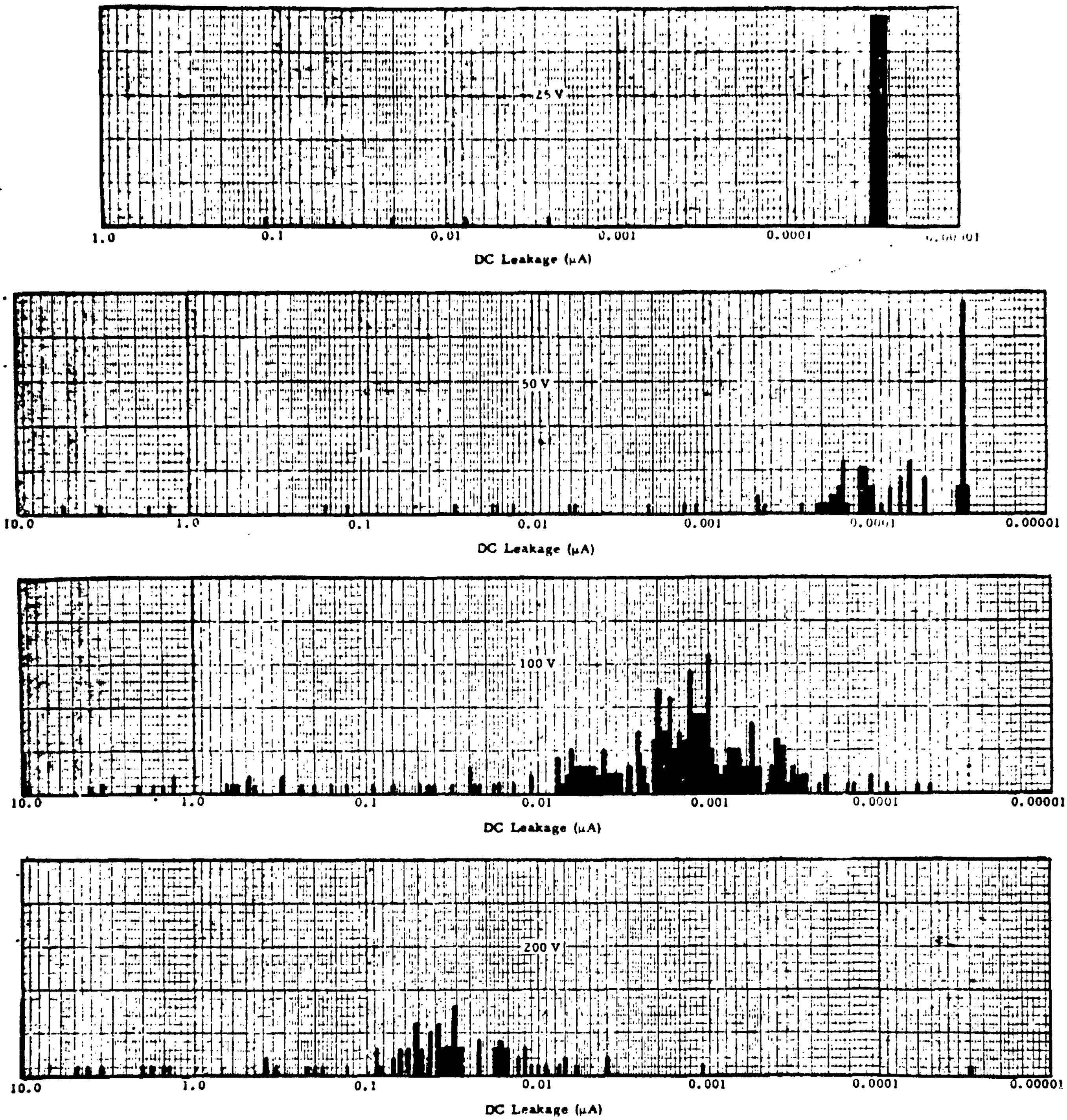
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 85°C 25,000 HOUR LIFE TEST
FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 6S9205)

Figure 97



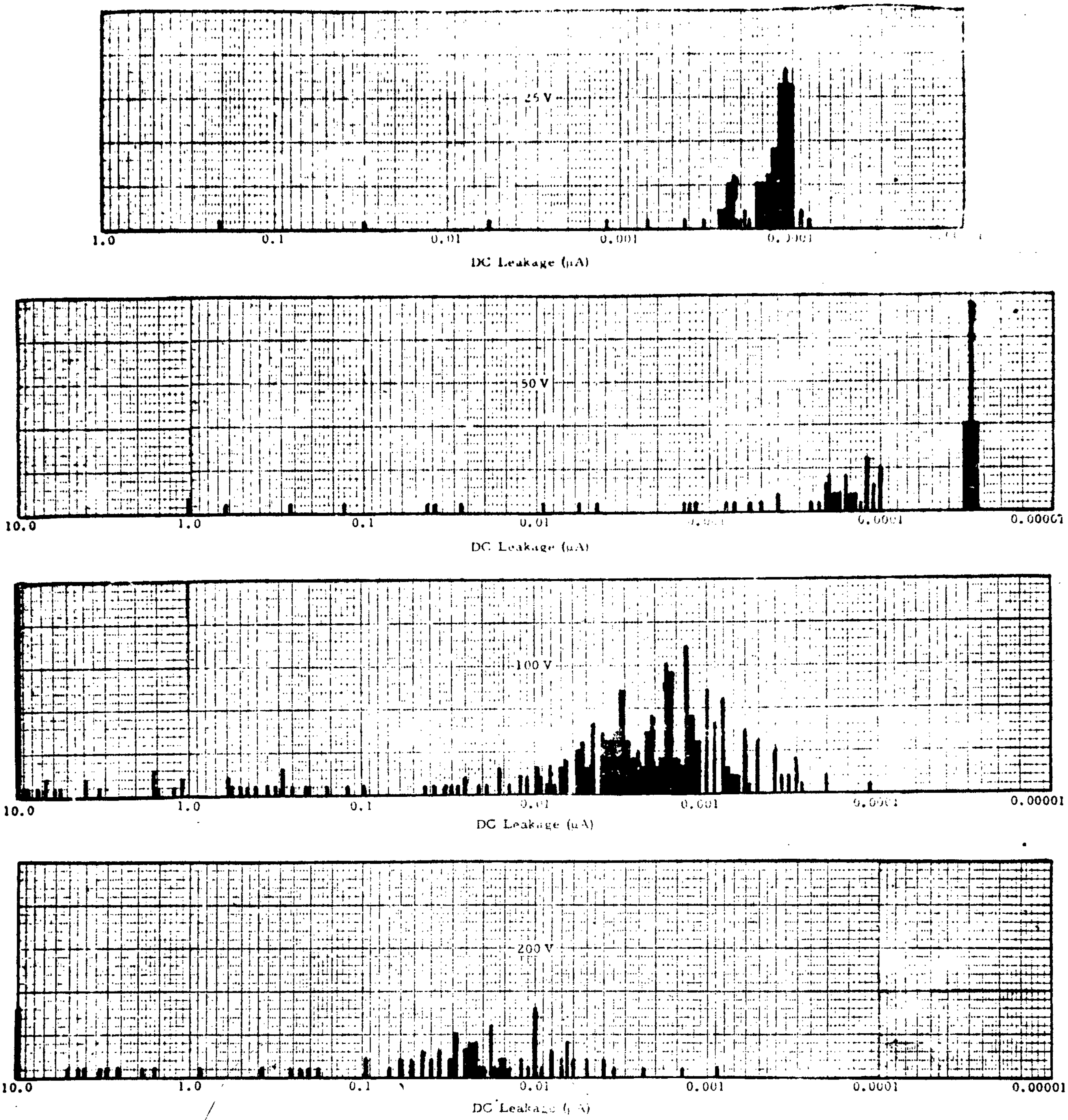
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 125°C 10,000 HOUR LIFE TEST
FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 6S9205)

Figure 98



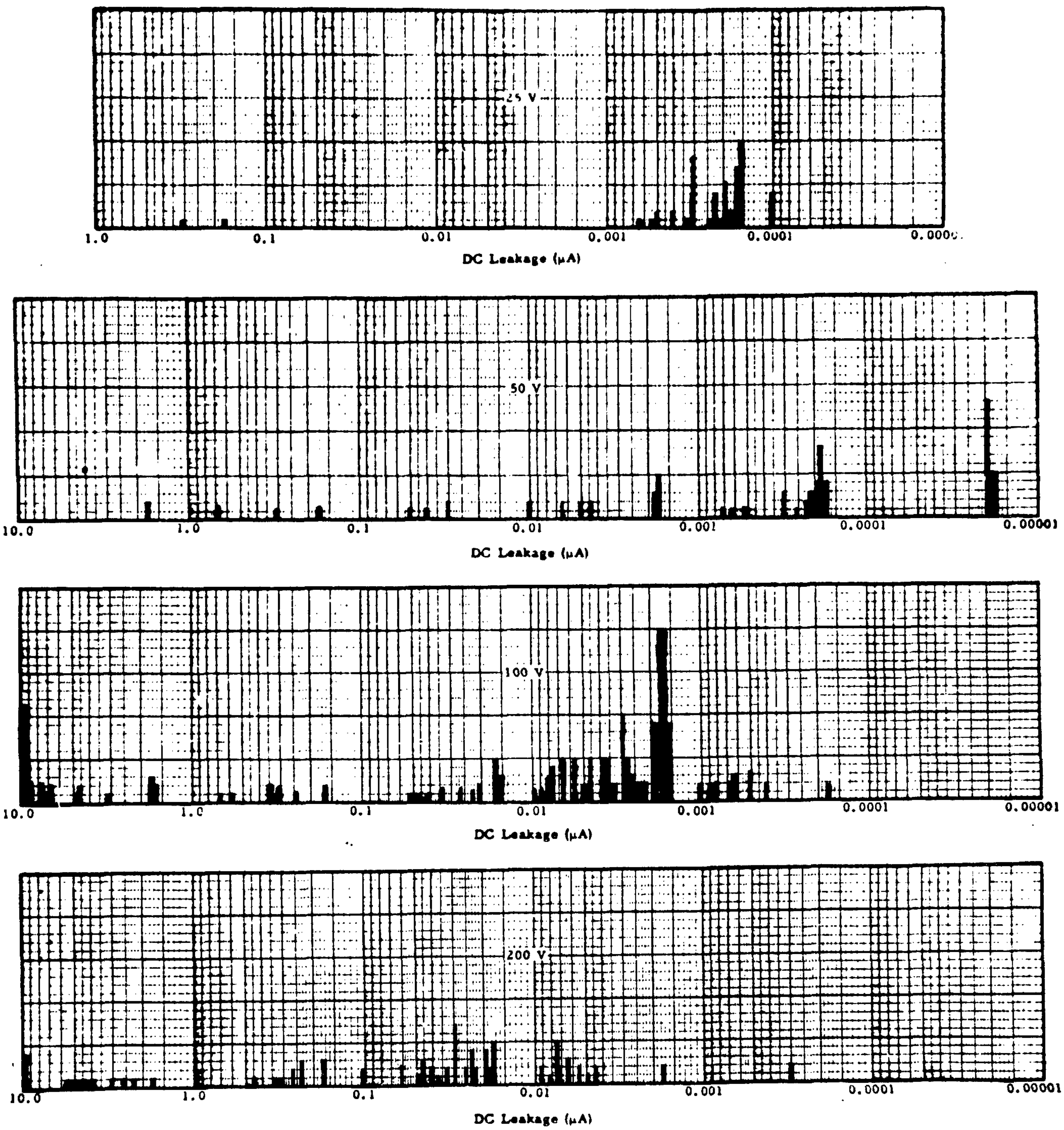
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 125°C 15,000 HOUR LIFE TEST
FOR 0.01 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 6S9205)

Figure 99



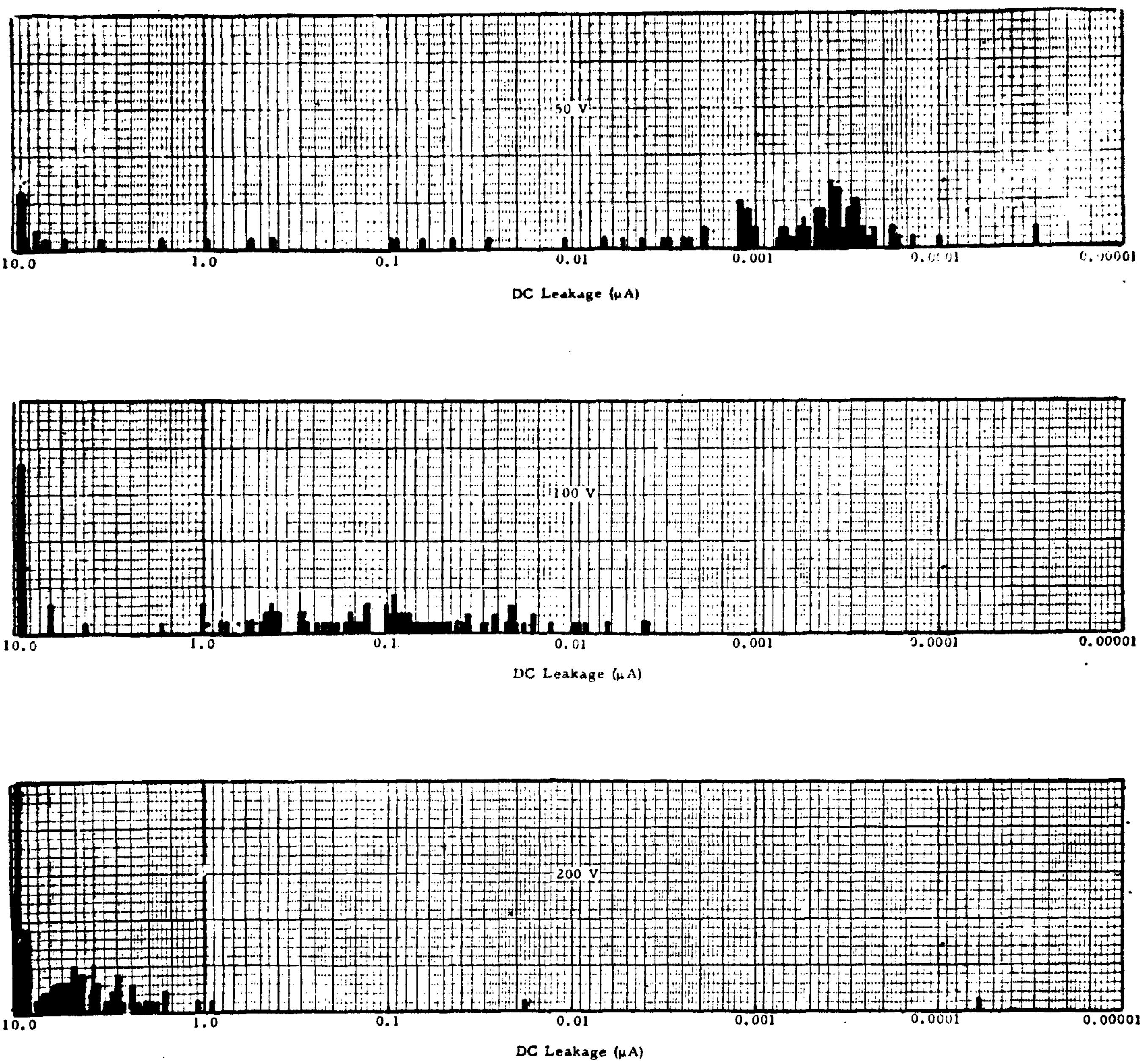
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 125°C 20,000 HOUR LIFE TEST FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 6S9205)

Figure 100



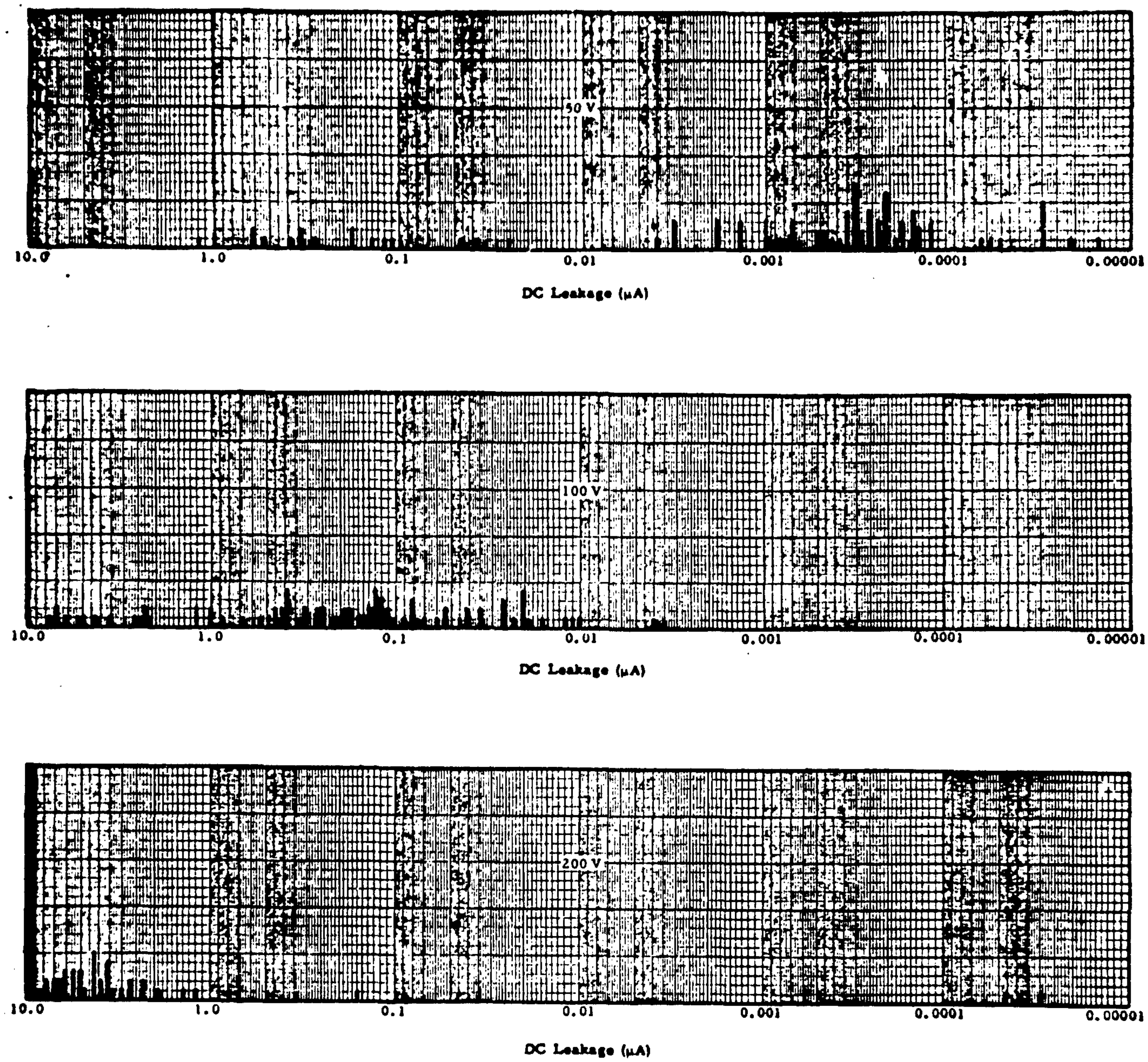
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 125°C 25,000 HOUR LIFE TEST
FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (6S9205)

Figure 101



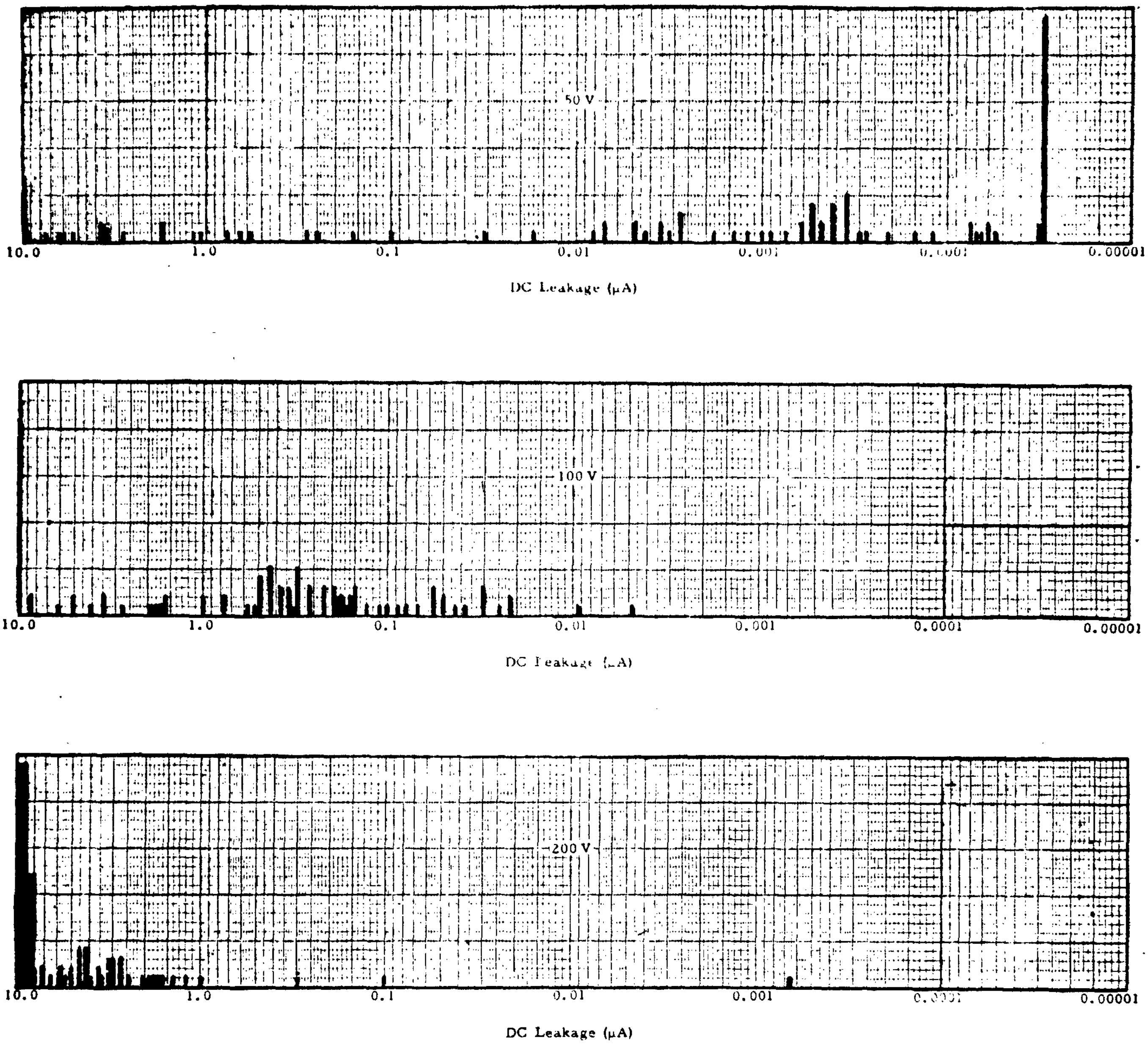
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 150°C 10,000 HOUR LIFE TEST
FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 6S9205)

Figure 102



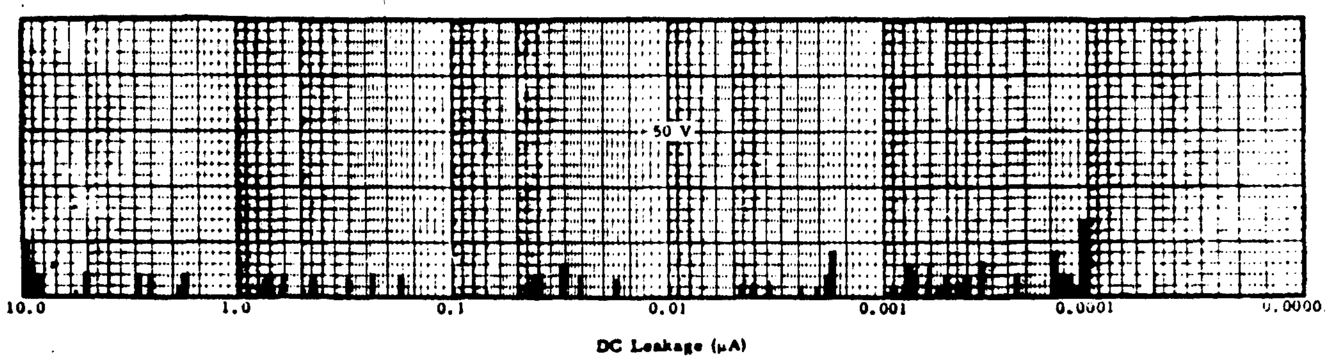
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 150°C 15,000 HOUR LIFE TEST
FOR 0.01 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 659205)

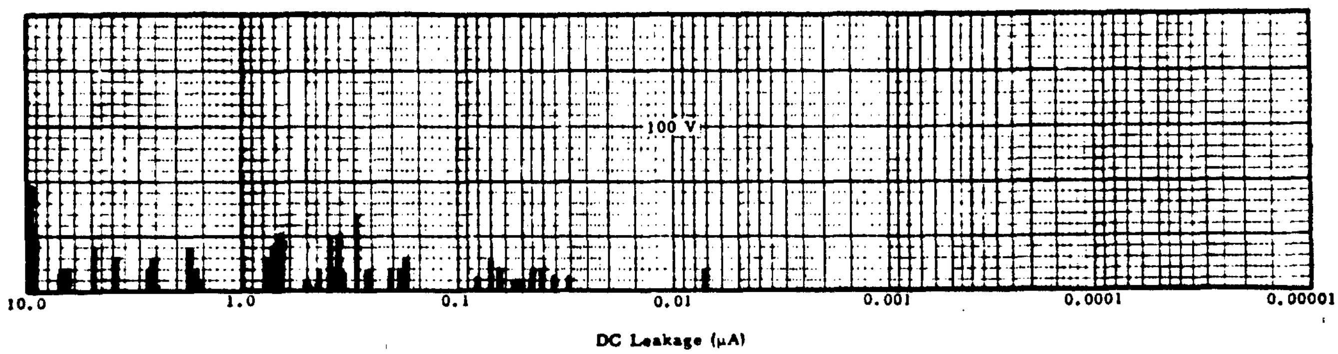
Figure 103

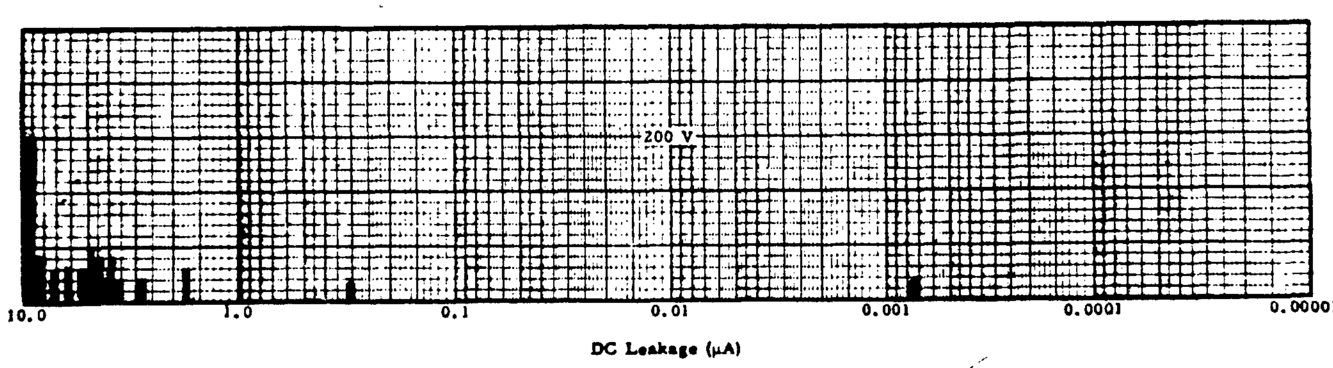


FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 150°C 20,000 HOUR LIFE TEST FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 659205)

Figure 104

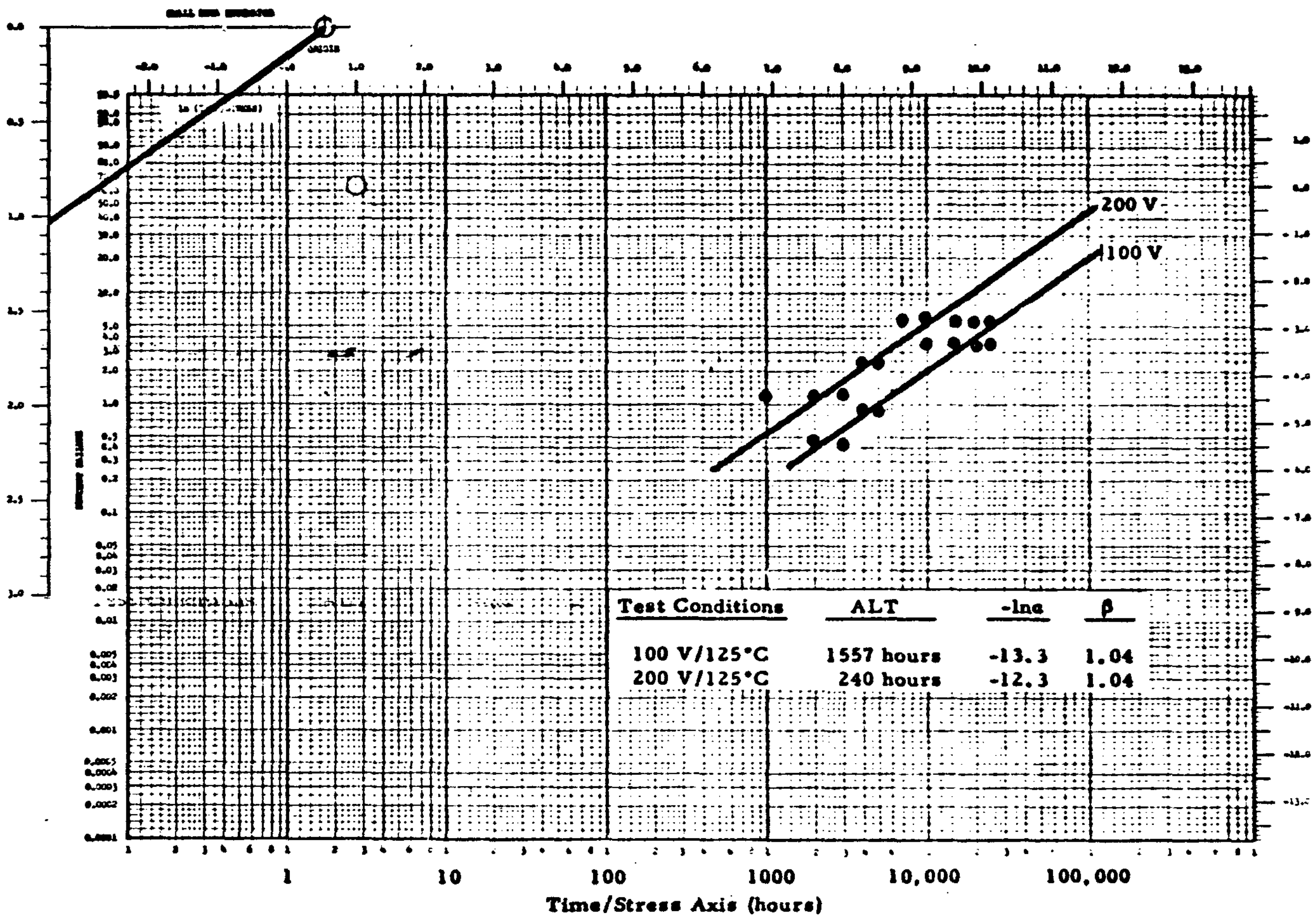






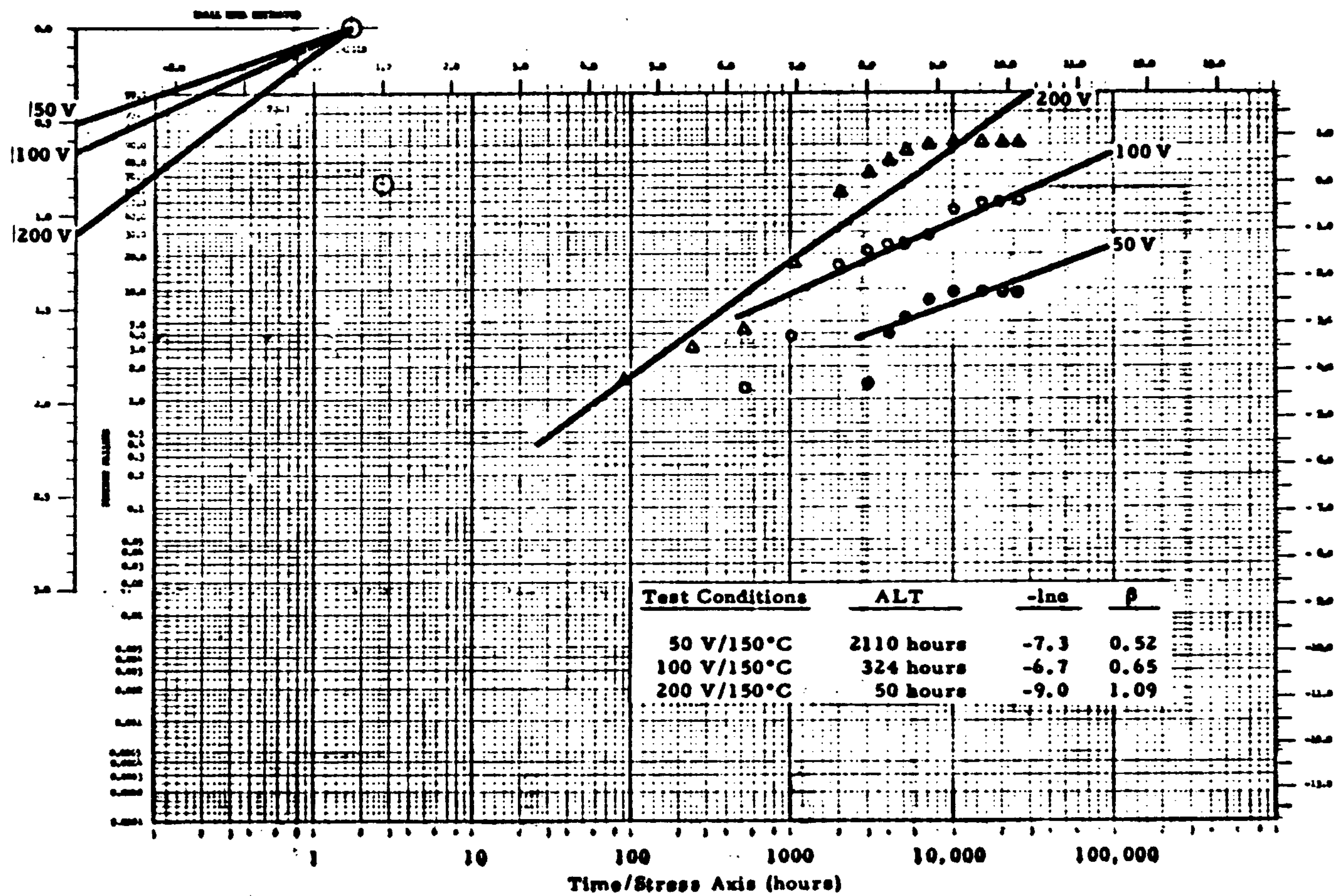
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 150°C 25,000 HOUR LIFE TEST FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (659205)

Figure 105



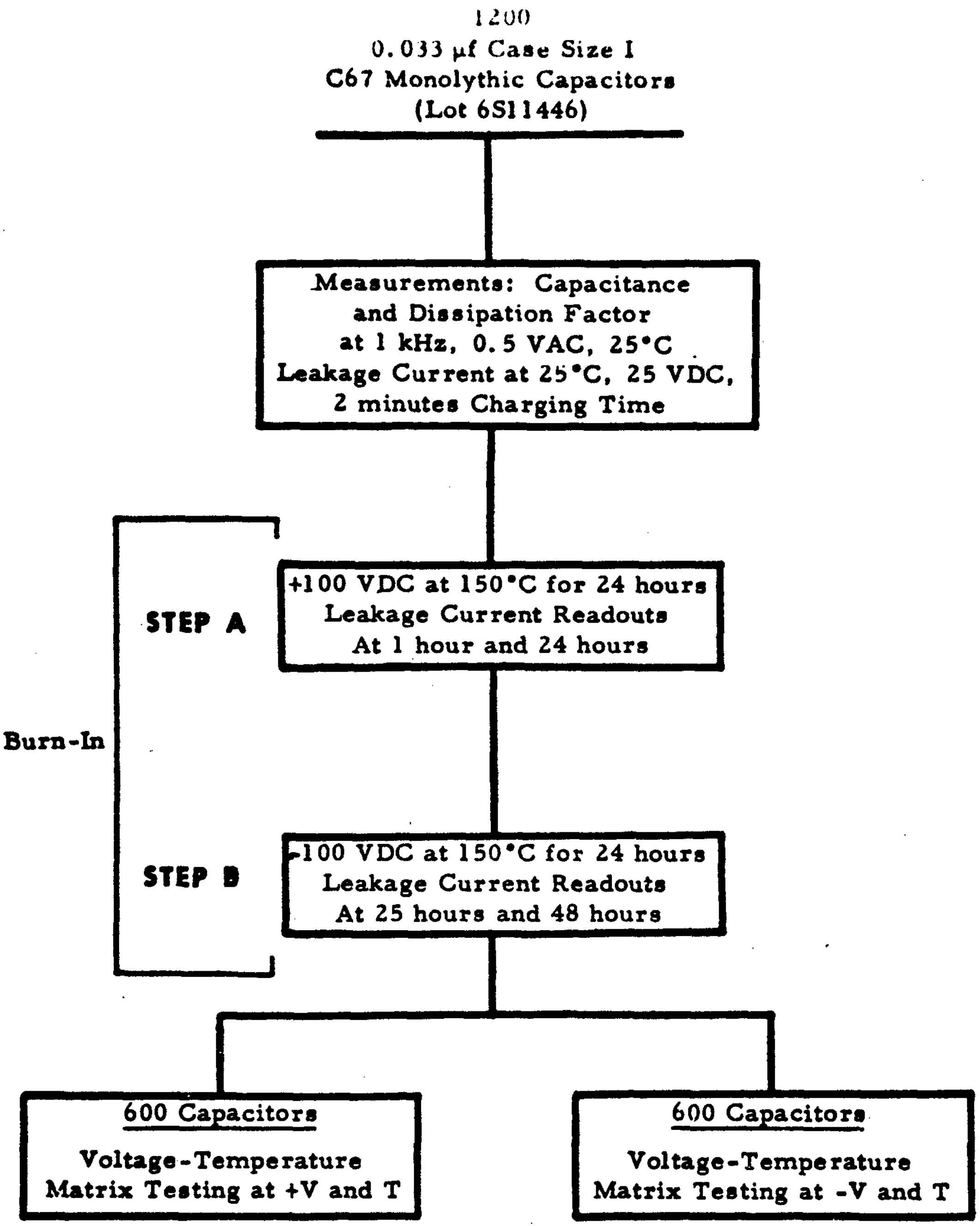
WEIBULL PROBABILITY PLOTS FOR 0.01 μF CAPACITORS PREDICTED NOT TO FAIL PRIOR TO ALT

Figure 106



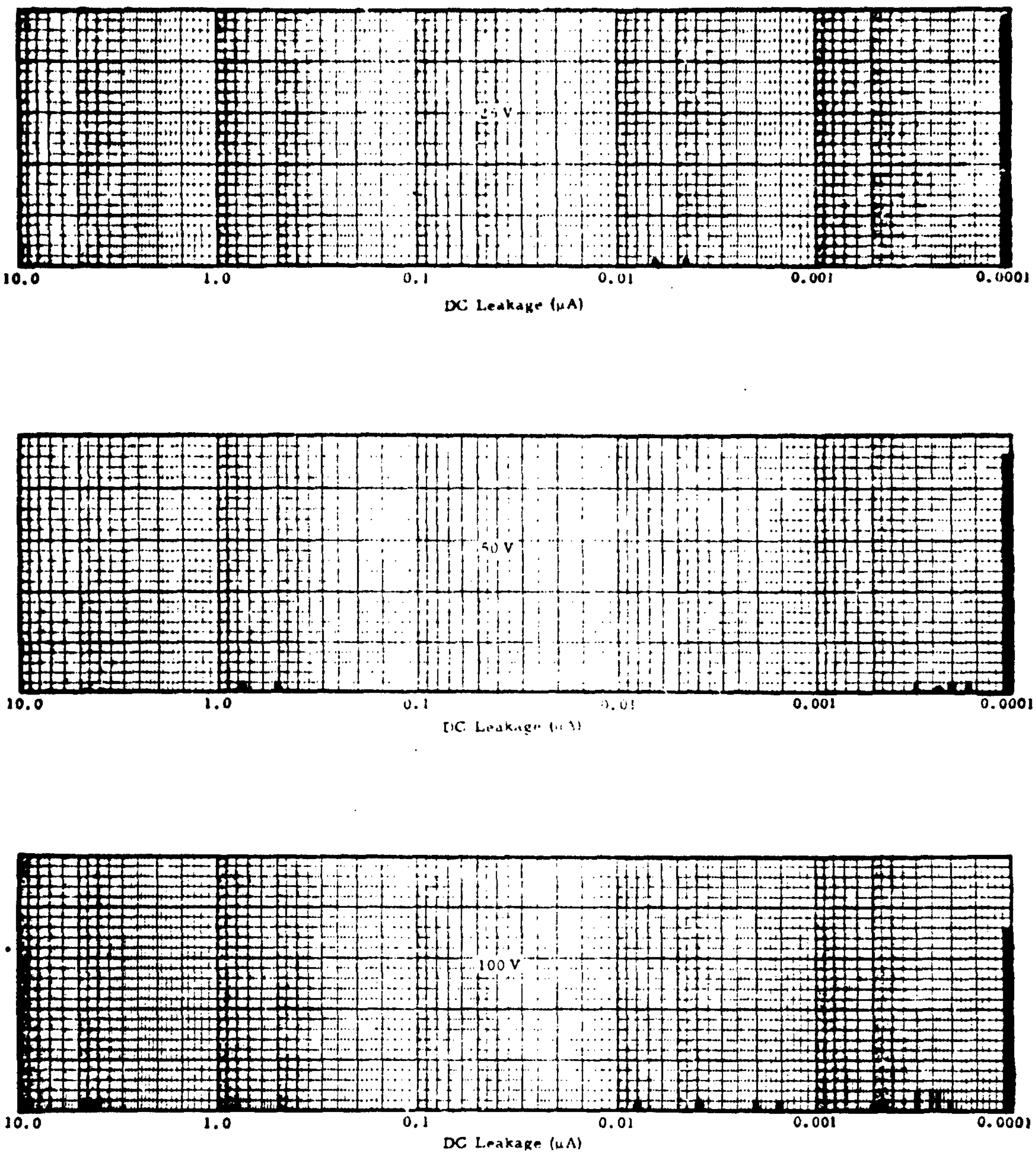
WEIBULL PROBABILITY PLOTS FOR 0.01 μF CAPACITORS PREDICTED NOT TO FAIL PRIOR TO ALT

Figure 107



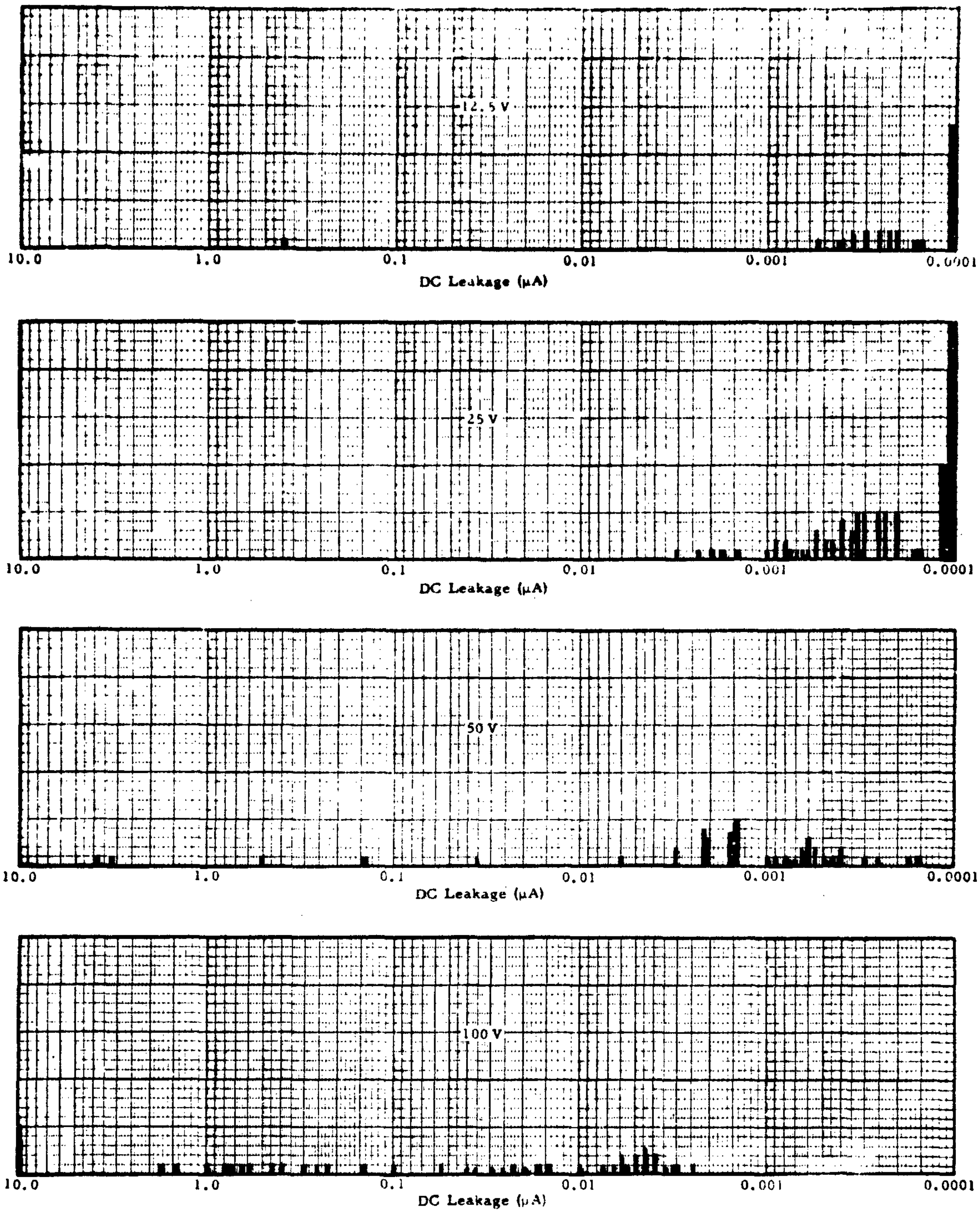
OUTLINE OF SECOND LIFE TEST MATRIX
FOR 0.033 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS

Figure 108



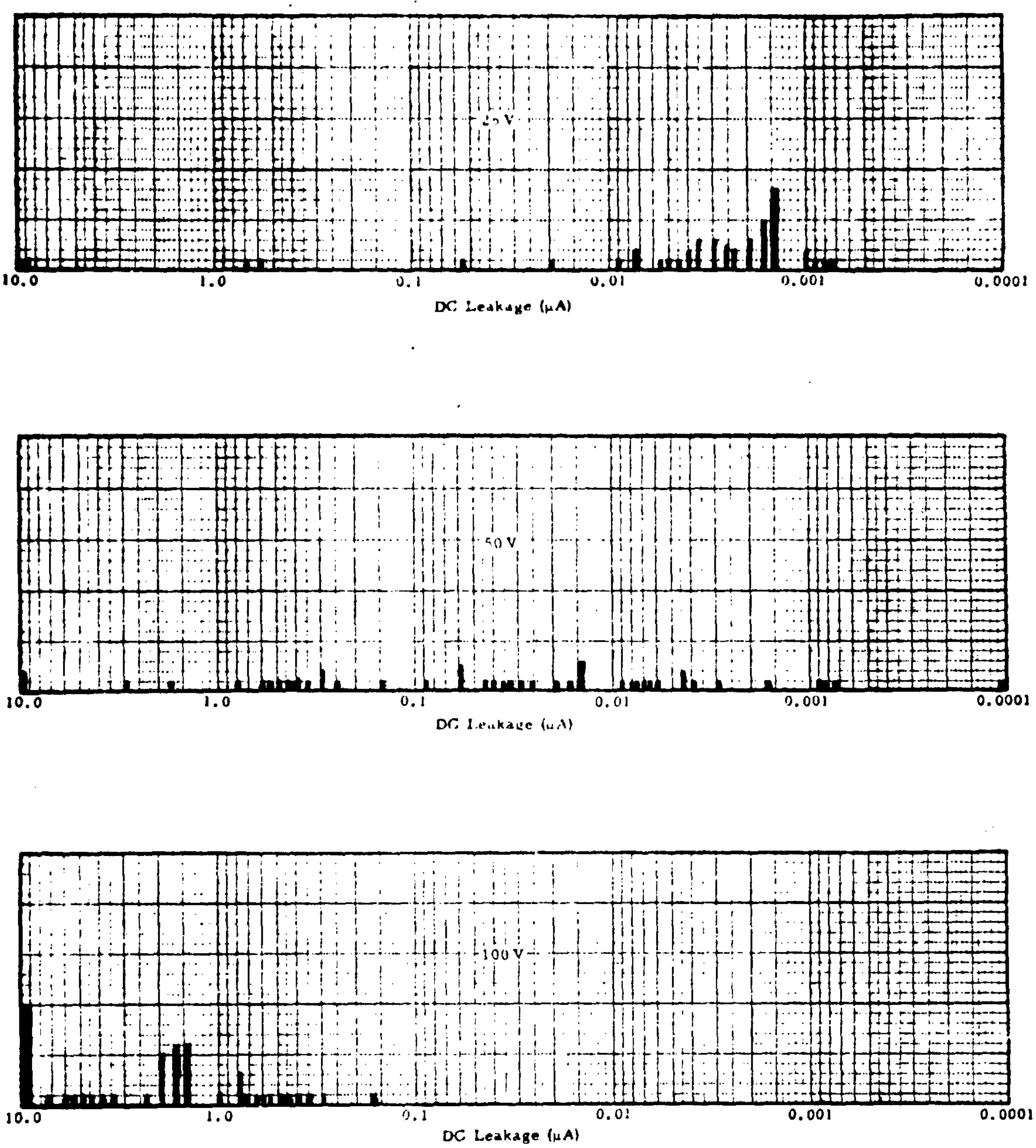
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 85°C 10,000 HOUR LIFE TEST FOR 0.033 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS

Figure 109



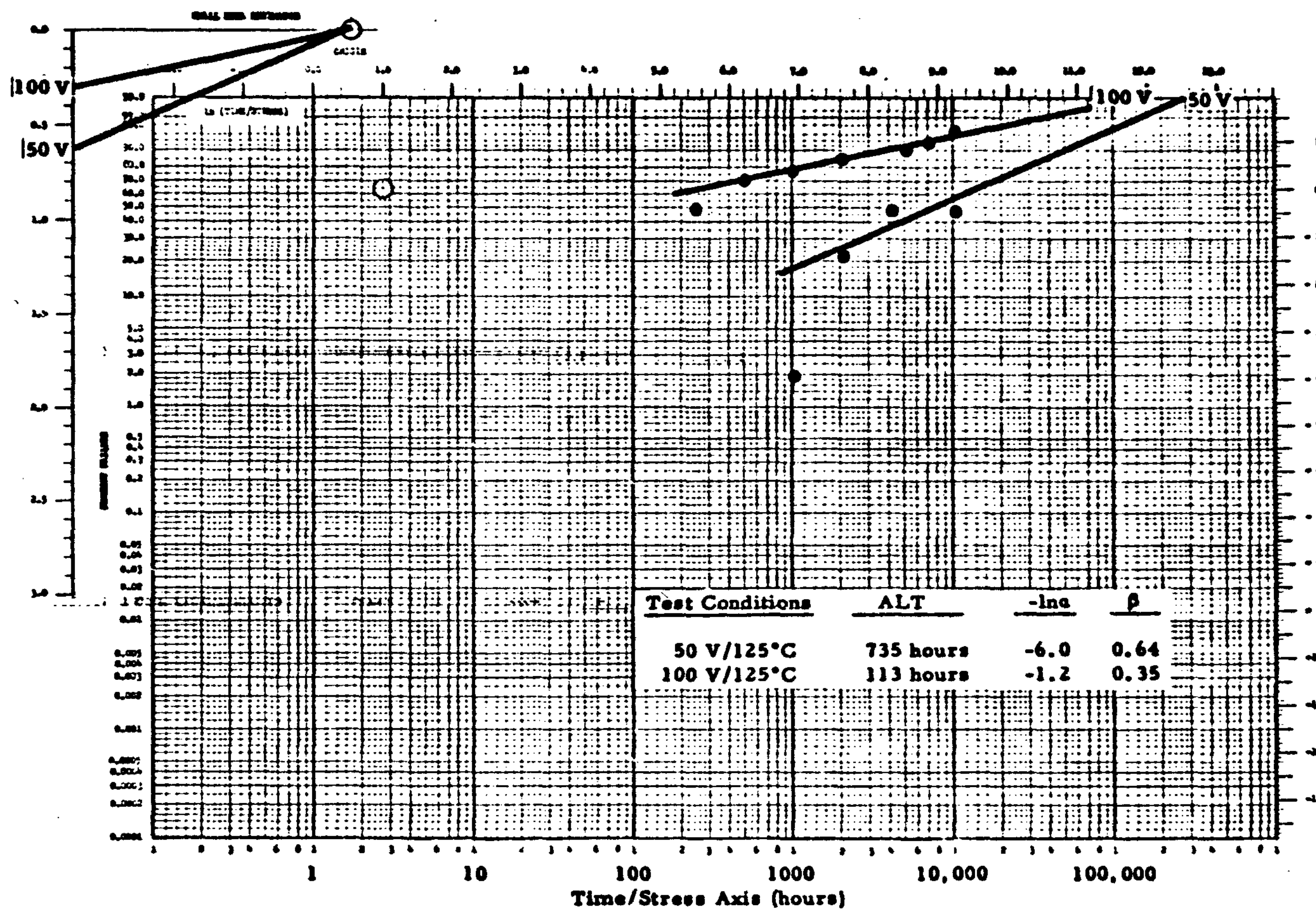
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 125°C 10,000 HOUR LIFE TEST FOR 0.033 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS

Figure 110



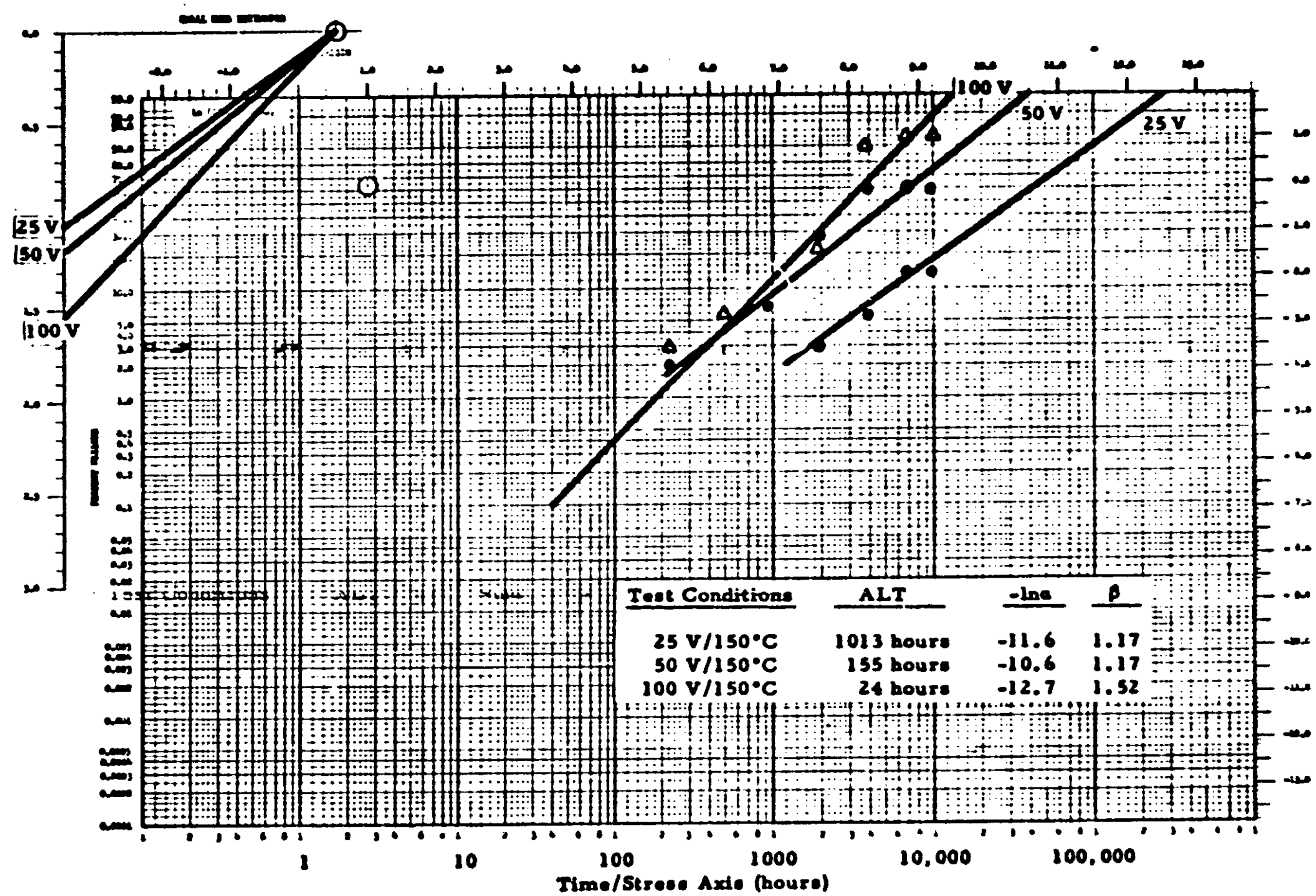
FREQUENCY DISTRIBUTION OF LEAKAGE CURRENT ON 150°C 10,000 HOUR LIFE TEST FOR 0.033 µF C67 CASE SIZE I MONOLYTHIC CAPACITORS

Figure 111



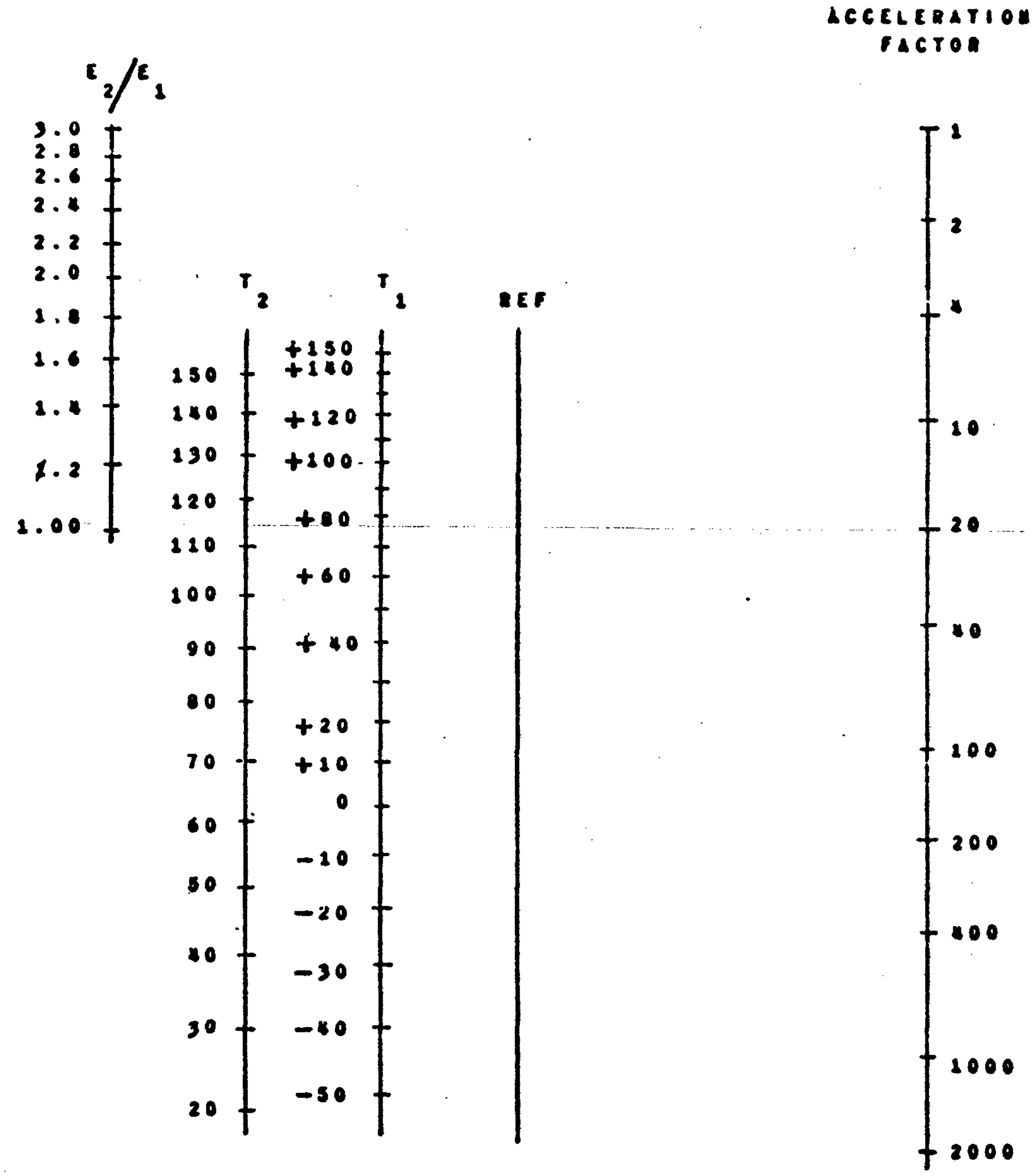
WEIBULL PROBABILITY PLOTS FOR 0.033 μF CAPACITORS PREDICTED NOT TO FAIL PRIOR TO ALT

Figure 112



WEIBULL PROBABILITY PLOTS FOR 0.033 μF CAPACITORS PREDICTED NOT TO FAIL PRIOR TO ALT

Figure 113



NOMOGRAM OF ACCELERATION EQUATION
Figure 114

TABLE I

OXYGEN CONCENTRATION CELL EXPERIMENTS

$Ag, O_2\ (p_1)$ | Ceramic C67 | $O_2\ (p_2)$, Ag

$O_2 + 4\bar{e} \quad 2O^{2-}$, where n = 4.

For a purely ionic conductor, the EMF produced by the above reaction may be calculated from the Nernst Equation.

i.e.,
$$E_i = \frac{-RT}{nF} \ln \frac{p_2}{p_1}$$

If the conductivity is of a mixed nature, the measured EMF is given by:

$$E = E_i\,(1 - \bar{t}_e - \bar{t}_p)$$

where $\bar{t}_e$ and $\bar{t}_p$ are the average transport numbers of electrons and holes, respectively.

<u>Measured Potentials, and the Percentage Ionic Conduction, for Unreliable Non-Ohmic C67 Ceramic</u>

T°C	p_1 (ATM) (O_2)	p_2 (ATM) (O_2)	E (mV)	< E > (mV)	E_i (mV)	Percent Ionic Conductivity
250	1.0	0.01	+33.5	33.5	51.9	64.5
	0.01	1.0	-33.5			
200	1.0	0.01	+29.5	30.3	46.8	64.7
	0.01	1.0	-31.0			
150	1.0	0.01	+24.8	24.7	42.0	58.8
	0.01	1.0	-24.5			

TABLE II

LIFE TEST PERFORMANCE OF CASE SIZE I C67 MONOLYTHIC UNITS AT 85°C AND 105°C

Unit No.	t_p (Min) At 185 VDC, 150°C	R_p (MΩ) At 185 VDC, 150°C	Resistance (MΩ) At 100 VDC, 85°C		Resistance (MΩ) At 200 VDC, 85°C			Resistance (MΩ) at 200 VDC, 105°C				Assuming g = 5 Calculated Lifetime* at 105°C, 200 VDC (Hr)
			MΩ at 24 Hr	MΩ at 340 Hr	MΩ at 48 Hr	MΩ at 600 Hr	MΩ at 1500 Hr	MΩ at 24 Hr	MΩ at 500 Hr	MΩ at 1300 Hr	MΩ at 2350 Hr	
583-16	1.3	18,200	>330,000	>330,000	330,000	125,000	21,500	5,880	46	23	11	
583-17	8.5	38,100	>330,000	>330,000	>660,000	>660,000	182,000	50,000	834	52	11	1.5
583-18	11	127,000	>330,000	>330,000	>660,000	>660,000	>660,000	445,000	286,000	29,400	2,980	
583-341	270	1,880,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	20
583-24	120	1,030,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	13,300	4,770	3,110	
583-26	28	555,000	>330,000	>330,000	>660,000	573,000	286,000	125,000	3,850	181	33	
583-27	344	1,110,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	440,000	
583-28	15	580	>330,000	>330,000	>660,000	>660,000	286,000	33,000	318	64	40	940
583-29	82	844,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	18,000	2,860	360	10
583-30	300	1,030,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	500,000	156,000	
583-31	240	1,290,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	5,560	4,000	330	
583-32	268	1,440,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	400,000	11,100	1,660	
583-33	105	1,030,000	>330,000	>330,000	364,000	45,000	3,640	2,540	286	95	82	270
583-34	22	197,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	400,000	77,000	6,650	
583-35	390	1,630,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	
427-11	330	3,000,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	
427-12	270	2,420,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	
427-15	120	1,830,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	500,000	250,000	
427-16	480	3,320,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	360
427-74	330	3,510,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	
427-75	346	2,740,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	
449-1	510	3,330,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	
449-2	480	3,210,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	1,800
449-3	480	2,720,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	
449-4	480	3,380,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	1,530
449-5	480	3,450,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	
449-6	480	2,640,000	>330,000	>330,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	>660,000	

*Failure is resistance less than 100 MΩ.

TABLE III

THIRTY-TWO THOUSAND HOURS LIFE TESTING SUMMARY FOR 0.01μF C67 CASE SIZE I MONOLYTHIC CAPACITORS (LOT 830 ALT: 1000 HRS. 200 VDC, 125°C)

Conditions	Time Hours	Cell A 29 Capacitors d_t	Cell A Failure	Cell B 24 Capacitors d_t	Cell B Failure	Cell C 24 Capacitors d_t	Cell C Failure	Cell D 22 Capacitors d_t	Cell D Failure	Cell E 23 Capacitors d_t	Cell E Failure
200 V, 125°C	24	0	0	0	0	2	0	1	1	0	0
200 V, 125°C	1000	0	0	0	0	2	0	1	1	0	0
200 V, 125°C	2300	0	0	0	0	2	0	1	1	0	0
400 V, 125°C	24	0	0	0	0	2	0	1	1	0	0
400 V, 125°C	1100	0	0	2	0	2	0	1	1	0	0
400 V, 125°C	6100	0	0	4	1	2	0	3	1	1	0
400 V, 125°C	13000	2	1	5	2	3	0	4	2	2	0
400 V, 125°C	19000	2	1	8	3	5	0	6	4	4	1
400 V, 125°C	24000	2	2	9	5	6	1	8	5	6	4
400 V, 125°C	30000	5	3	11	5	9	2	12	7	10	5

Failure is defined as resistance being less than 100 MΩ at test conditions.

d_t means capacitor is beyond the onset-of-degradation. A failure is also counted with the capacitors beyond the onset-of-degradation.

TABLE IV

LISTING OF PROPERTIES OF 0.033μF, C67 CERAMIC CASE SIZE I MONOLYTHIC CAPACITORS

(Pre-Production Sampling Lot No. 6S-11446, 1.0 mil Dielectric Layers)

Unit No.	Capacitance 1 kc/sec 0.01 V μF	Dissipation Factor (%)	Resistance 45 V, 2 min 25°C (MΩ)	RC Product 25°C MΩ-μF
1000	0.0372	1.10	300,000	11,200
1001	0.0424	1.08	264,000	11,200
1002	0.0426	1.20	264,000	11,200
1003	0.0381	1.13	300,000	11,400
1004	0.0357	1.08	346,000	12,300
1005	0.0429	1.17	280,000	12,000
1006	0.0428	1.18	265,000	11,300

Megohms Resistance at 95 VDC, 150°C Life Performance Test Conditions

Elapsed Time (hr)	Unit No. 1000	Unit No. 1001	Unit No. 1002	Unit No. 1003	Unit No. 1004	Unit No. 1005	Unit No. 1006
3.6	22,600	15,300	11,800	12,600	22,600	13,100	18,300
7.2	21,100	13,700	10,500	12,200	20,200	11,800	17,200
24	22,600	15,800	11,100	12,800	22,600	12,800	18,300
55	18,200	10,500	7,900	10,000	17,200	10,000	14,400
146	17,900	320	8,600	9,500	17,300	10,000	13,500
200	16,400	25	7,900	9,500	16.300	9,500	10,500
342	13,700	9	6,300	7,900	13,100	7,900	3,700
560	13,600		5,600	7,300	14,800	7,900	870
726	13,200		350	6,800	13,600	7,900	590
896	9,500		240	4,700	10,500	6,300	390
1152	5,300		82	1,800	6,300	5,800	160
1297	5,900		86	1,400	6,300	3,650	130
1394	5,300		95	1,200	6,300	3,800	130

TABLE V

LIFE TEST MATRIX VOLTAGE/TEMPERATURE CONDITIONS AND READOUT SCHEDULE FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS

Number of Units at Each Voltage/Temperature Condition

		Temperature	
Voltage	85°C	125°C	150°C
25	---	100	---
50	100	100	100
100	100	300	100
200	100	100	100

Leakage Current Readouts Are Scheduled at 1, 48, 96, 240, 504, 1,008, 2,016, 3,024, 4,032, [illegible],040, 7,056, 10,080, 15,000, 20,000 and 25,000 hours.

TABLE VI

LIFE TEST RESULTS OF VOLTAGE TEMPERATURE MATRIX FOR 0.01 µF C67 CASE SIZE 1 MONOLYTHIC CAPACITORS PREDICTED NOT TO FAIL

1 Test Cell	2 Test Conditions	3 Assured Lifetimes	4 No. Units	5 No. Fails before ALT	6 No. Fails To 25000 Hrs.	7 (100V/125°C) Equivalency Factor *	8 Equivalent Unit Hours (4 x 7) **
1	50V/85°C	188845	73	‡	0	215	15695
2	100V/85°C	29042	78	‡	0	1375	107250
3	200V/85°C	4475	63	0	0	1575	99225
4	25V/125°C	30312	69	‡	0	595	41055
5	50V/125°C	10128	80	0	0	1580	126400
6	100V/125°C	1557	212	2	8	1557	326970
7	200V/125°C	240	79	0	5	1536	121344
8	50V/150°C	2110	74	1	7	1547	112368
9	100V/150°C	324	76	0	38	1523	115478
0	200V/150°C	50	65	3	59	1504	97610
TOTALS			869	6	117		1,163,395

Failure rate to ALT at arbitrary conditions (100V/125°C) with 90% confidence in %/1000 hours ------------- 0.89%

Failure rate to ALT at arbitrary conditions (100 V/125°C) with 90% confidence in %/1000 hours omitting 150°C cells unit hours and failures -- 0.64%

Failure rate to ALT at transistor circuitry conditions (25V/125°C) at 90% confidence in %/1000 hours -------- 0.021%

Failure rate to ALT at transistor circuitry conditions (25V/125°C) at 90% confidence in %/1000 hours omitting 150°C cells unit hours and failures -- 0.015%

* To ALT or 25000 hours, whichever is first.

** Column 8 is determined by the product of columns 4 and 7.

‡ ALT greater than 25,000 hours

TABLE VII

DISTRIBUTION OF CAPACITORS THAT WERE NOT FAILURES ON LIFE TEST (INSULATION RESISTANCE ABOVE 500Ω) AND PREDICTED AS FAILURES BY ONE OR MORE OF THE FAILURE CRITERIA

(0.01 μF)

VOLTAGE GROUP		25			50			100			200			TOTALS
TEST TEMPERATURE (°C)		85	125	150	85	125	150	85	125	150	85	125	150	
TEST CELL		---	4	---	1	5	8	2	6	9	3	7	0	
SINGLE * CRITERION (PAR. 3.6.2)	1	---	6	---	4	10	1	6	11	0	4	3	0	45
	2	---	8	---	16	14	0	8	27	0	7	4	0	84
	3	---	6	---	0	3	5	3	8	0	1	1	0	27
TOTALS			20		20	27	6	17	46	0	12	8	0	156
COMBINED ** CRITERIA (PAR. 3.6.2)	1 & 2	---	1	---	3	7	0	4	3	0	3	1	0	22
	2 & 3	---	0	---	0	0	0	0	0	0	0	0	0	0
	1 & 3	---	1	---	0	1	1	1	4	0	0	0	0	8
	1, 2 & 3	---	4	---	0	1	0	1	1	0	0	1	0	8
TOTALS			6		3	9	1	6	8	0	3	2	0	38

* If a capacitor failed more than one criterion it was listed only in the single criterion category at the first failure.

** Combined criteria categories are mutually exclusive.

TABLE VIII

DISTRIBUTION OF CAPACITORS THAT WERE FAILURES ON LIFE TEST (INSULATION RESISTANCE BELOW 500Ω) AND PREDICTED AS FAILURES BY ONE OR MORE OF THE FAILURE CRITERIA

(0.01 μF)

VOLTAGE GROUP		25			50			100			200			TOTALS
TEST TEMPERATURE (°C)		85	125	150	85	125	150	85	125	150	85	125	150	
TEST CELL		---	4	---	1	5	8	2	6	9	3	7	0	
SINGLE * CRITERION (PAR. 3.6.2)	1	---	4	---	1	5	13	2	22	11	7	8	12	85
	2	---	2	---	1	3	8	1	17	7	6	6	14	65
	3	---	1	---	0	2	4	0	3	3	1	2	9	25
TOTALS			7		2	10	25	3	42	21	14	16	35	175
COMBINED ** CRITERIA (PAR. 3.6.2)	1 & 2	---	1	---	1	2	8	1	13	5	5	5	6	47
	2 & 3	---	0	---	0	0	0	0	0	0	0	0	0	0
	1 & 3	---	0	---	0	0	3	0	1	3	0	0	4	11
	1, 2 & 3	---	1	---	0	1	0	0	2	0	1	1	2	8
TOTALS			2		1	3	11	1	16	8	6	6	12	66

* If a capacitor failed more than one criterion it was listed only in the category of first failure.

** The combined criteria categories are mutually exclusive.

TABLE IX

LIFE TEST RESULTS OF VOLTAGE TEMPERATURE MATRIX
FOR 0.01 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS
PREDICTED TO FAIL

1 Test Cell	2 Test Conditions	3 100V/125°C Equivalency Factor*	4 No. of Units	5 No. Fails Before ALT	6 Equivalent Unit Hours **
1	50V/85°C	215	27	1	5590
2	100V/85°C	1375	22	1	28875
3	200V/85°C	1575	37	7	47250
4	25V/125°C	595	31	4	16065
5	50V/125°C	1580	20	4	25280
6	100V/125°C	1557	88	13	116775
7	200V/125°C	1536	21	6	23040
8	50V/150°C	1547	26	13	20111
9	100V/150°C	1523	24	7	25891
0	200V/150°C	1504	35	6	43616
TOTALS			331	62	352493

Failure rate to ALT at arbitrary conditions (100V/125°C) at 90% confidence in %/1000 hours -------------------------------------- 21.0%

*To ALT or 25,000 hours whichever is less.

**Column 6 is determined by the product of columns 3 and 4.

Failure rate to ALT at transistor circuitry conditions (125°/25V) at 90% confidence in %/1000 hours -------------------------------------- 0.48%

TABLE X

LIFE TEST MATRIX VOLTAGE/TEMPERATURE CONDITIONS AND READOUT SCHEDULE FOR 0.033 μF C67 CASE SIZE I MONOLYTHIC CAPACITORS

Number of Units at Each Voltage/Temperature Condition

Voltage	Temperature 85°C	125°C	150°C
12.5	---	100	---
25	100	300	100
50	100	100	100
100	100	100	100

Leakage Current Readouts are Scheduled at 24, 96, 240, 504, 1,008, 2,016, 4,032, 7,056 and 10,080 hours.

TABLE XI

LIFE TEST RESULTS OF VOLTAGE TEMPERATURE MATRIX
FOR 0.033 μF CASE SIZE I MONOLYTHIC CAPACITORS
NOT PREDICTED TO FAIL

1 Test Cell	2 Test Condition	3 Assured Lifetime	4 No. Units	5 No. Fails to ALT	6 No. Fails to 10,000 Hours	7 (25V/125°C) Equivalency Factor*	8 Equivalent Unit Hours **
1	25V/85°C	89550	85	‡	0	554	47090
2	50V/85°C	13781	97	‡	0	3548	344156
3	100V/85°C	2120	93	0	0	4921	457653
4	12.5V/125°C	31038	91	‡	0	1572	143052
5	25V/125°C	4775	297	0	30	4775	1188297
6	50V/125°C	735	99	0	48	4704	465696
7	100V/125°C	113	97	0	94	4769	462593
8	25V/150°C	1013	97	0	14	4761	461817
9	50V/150°C	155	98	0	60	4662	456876
0	100V/150°C	24	95	0	93	4760	452200
TOTALS			1149	0	339		4479430

Failure rate to ALT at transistor circuitry conditions (25V/125°C) with 90% confidence in %/1000 hours ---------- 0.086%

Failure rate to ALT at transistor circuitry conditions (25V/125°C) with 90% confidence in %/1000 hours omitting 150°C cells unit hours and failures ---------- 0.12%

* To ALT or 10080 hours, whichever is first.

**Column 8 is determined by the product of columns 4 and 7.

‡ ALT greater than 10,000 hours

TABLE XII

DISTRIBUTION OF CAPACITORS THAT WERE NOT FAILURES ON LIFE TEST PRIOR TO ALT (INSULATION RESISTANCE ABOVE 500Ω) AND PREDICTED AS FAILURES BY ONE OR MORE OF THE FAILURE CRITERIA

(0.033 μF)

VOLTAGE GROUP		12.5			25			50			100			TOTALS
TEST TEMPERATURE (°C)		85	125	150	85	125	150	85	125	150	85	125	150	
TEST CELL		---	4	---	1	5	8	2	6	9	3	7	0	
SINGLE *	1	---	1	---	1	0	0	0	0	1	0	0	0	3
CRITERION	2	---	2	---	4	3	0	1	0	0	3	0	0	13
(PAR. 3.7.2)	3	---	2	---	6	0	1	0	0	0	1	0	0	10
TOTALS		---	5	---	11	3	1	1	0	1	4	0	0	26
	1+2	---	1	---	0	0	0	0	0	0	0	0	0	1
COMBINED ** CRITERIA	2+3	---	1	---	0	0	0	0	0	0	0	0	0	1
(PAR. 3.7.2)	1+3	---	0	---	0	0	0	0	0	0	0	0	0	0
	1+2+3	---	0	---	1	0	0	0	0	0	0	0	0	1
TOTALS		---	2	---	1	0	0	0	0	0	0	0	0	3

* If a capacitor failed more than one criterion it was listed only in the single category in the order of the first failure.

** The combined criteria categories are mutually exclusive.

TABLE XIII

DISTRIBUTION OF CAPACITORS THAT WERE FAILURES ON LIFE TEST PRIOR TO ALT (INSULATION RESISTANCE BELOW 500Ω) AND PREDICTED AS FAILURES BY ONE OR MORE OF THE FAILURE CRITERIA

(0.033 μF)

VOLTAGE GROUP		12.5			25			50			100			TOTALS
TEST TEMPERATURE °C		85	125	150	85	125	150	85	125	150	85	125	150	
TEST CELL		---	4	---	1	5	8	2	6	9	3	7	0	
SINGLE * CRITERION (PAR. 3.7.2)	1	---	1	---	2	0	0	0	0	0	1	1	2	7
	2	---	2	---	1	0	0	2	0	1	1	0	1	8
	3	---	1	---	1	0	2	0	1	0	1	2	2	10
TOTALS		---	4	---	4	0	2	2	1	1	3	3	5	25
COMBINED ** CRITERIA (PAR. 3.7.2)	1+2	---	0	---	0	0	0	0	0	0	0	0	0	0
	2+3	---	1	---	0	0	0	0	0	0	0	0	0	1
	1+3	---	0	---	0	0	0	0	0	0	0	1	1	2
	1+2+3	---	0	---	1	0	0	0	0	0	1	0	1	3
TOTALS			1		1	0	0	0	0	0	1	1	2	6

* If a capacitor failed more than one criterion it was listed only in the single category in the order of the first failure.

** The combined criteria categories are mutually exclusive.

TABLE XIV

LIFE TEST RESULTS OF VOLTAGE TEMPERATURE MATRIX FOR 0.033 µF CASE SIZE 1 MONOLYTHIC CAPACITORS PREDICTED TO FAIL

1 Test Cell	2 Test Condition	3 25V/125°C Equivalency Factor *	4 No. of Units	5 No. Fails to ALT *	6 Equivalent Unit Hours (3 x 4) **
1	25V/85°C	554	15	1	8310
2	50V/85°C	3548	3	2	10644
3	100V/85°C	4921	7	1	34447
4	12.5V/125°C	1572	9	2	14148
5	25V/125°C	4001	3	0	12003
6	50V/125°C	4704	1	0	4704
7	100V/125°C	4769	3	0	14307
8	25V/150°C	4761	3	1	14283
9	50V/150°C	4662	2	0	9324
0	100V/150°C	4760	5	1	23800
TOTALS			51	8	145970

Failure rate to ALT at transistor circuitry conditions (25V/125°C) at 90% confidence in %/1000 hours-------------8.8%

ALT values presented in Table XI

* To ALT or 10,080 hours, whichever is less

** Column 6 is determined by the product of columns 3 and 4

SECTION 4

CONCLUSIONS

Research shows that during a life test, the C67 ceramic subminiature capacitor DC resistance begins at a high level where it remains or increases slightly before it begins to decrease over several orders of magnitude. The decrease of resistance with time is labeled degradation and the time at which degradation commences is labeled onset-of-degradation. The time interval until the onset-of-degradation is dependent inversely on the applied field and temperature. A capacitor that is tested to the onset-of-degradation, and some amount beyond, may suffer only reversible damage. The damage is remedied by retesting for the same time period at the same conditions with reversed voltage. This produces a rejuvenated capacitor. If the time to the onset-of-degradation (t_2) is known at conditions E_2 and T_2, then time to the onset-of-degradation t_1 for conditions E_1 and T_1 can be calculated using a formula experimentally obtained from C67 MONOLYTHIC ceramic capacitors.

$$t_1 = t_2 \left[\left(\frac{E_2}{E_1}\right)^{2.7}\right] \exp \left[\left(\frac{0.90}{0.0000862}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

where:

E_1 and E_2 are voltages and T_1 and T_2 are temperatures in degrees Kelvin.

The above formula may be used for the selection of long life capacitors. If high reliability performance (zero failures on life test) is desired for given conditions of voltage and temperature for a given period of time, it must be established that the requirement is not beyond a time span when irreversible damage results for the material in a specific capacitor design. To obtain this answer in a short period of time, a sampling of the capacitors should be tested at more severe conditions of temperature and the voltage and resistance monitored (to find the onset-of-degradation). The period of time for this should be calculated by using the above formula.

Once it is determined that most of the capacitors have onset-of-degradation equal to or greater than the requirements, then the conditions of voltage, temperature and time can be established for capacitor acceptance or rejection. Acceptable capacitors are those not exhibiting degradation (indicating reversible damage) during voltage selection testing. Unacceptable capacitors are those exhibiting degradation (indicating irreversible damage). The acceptable capacitors therefore have a guaranteed or assured lifetime (ALT). The specific selected conditions are to be used to calculate ALT for different levels of voltage and temperature operation.

The above deductions from research were tested on two capacitor lots (0.01 µF and 0.033 µF) containing 1200 parts in each. The duration of life testing at several conditions of temperature and voltage was 25,000 hours in the case of the 0.01 µF capacitors and 10,000 hours in the case of the 0.033 µF capacitors. The individual capacitors in each lot were subjected to voltage selection testing for a specific period of time at 150°C. The capacitors were identified as either having received irreversible damage or reversible damage. ALT was calculated for the capacitors at all life test conditions. The life test behavior of the capacitors was evaluated as two groups:

1. Capacitors which passed voltage selection testing criteria (reversibly damaged and rejuvenated).

2. Capacitors that did not pass (irreversibly damaged)

A total of 869 capacitors rated at 0.01 µF were acceptable according to the voltage selection testing criteria. These capacitors had a failure rate (after normalizing data) at 125°C and 25 VDC to ALT (30,[illegible]00 hours) of 0.021% per 1000 hours. The 331 capacitors which were predicted to fail before ALT had a failure rate of 0.48% per 1000 hours.

The failure rate of the 1149 capacitors rated at 0.033 µF which were predicted not to fail during 4775 hours (ALT) at 125°C, 25 VDC was 0.086% per 1000 hours. The true failure rate may be less because zero failures were generated prior to ALT. The 51 capacitors predicted to fail prior to ALT showed a failure rate of 8.8% per 1000 hours.

Although none of the test conditions attained the objecti[illegible] of 0.001%/1000 hours failure rate at arbitrary transistor circuitry conditions (25V/125°C), some conditions of the testing program demonstrated their best attainable failure rate to ALT given the number of units (zero failures noted, Tables VI and XI).

SECTION 5

IDENTIFICATION OF PERSONNEL

The following is a listing of technical personnel and the hours they have spent on this contract:

C. Bailey	9.0	M. Malanga	22.0
D. Begnoche	43.0	R. Massey	14.0
C. Belouin	28.5	A. McAdams	4.0
E. Benoit	40.0	P. Milenski	126.0
W. Brierly	281.0	G. Morse	208.5
L. Burdick	117.0	G. Olsen	15.5
O. Buyomaster	8.0	D. Payne	750.5
B. Cirone	5.0	W. Pfister	7.0
P. Delisle	38.5	T. Prokopowicz	691.0
G. Dyndor	77.0	D. Reid	61.0
J. Dziok	1.5	F. Rotolo	85.0
N. Eror	80.0	F. Schoenfeld	221.0
W. Estes	328.2	J. Shea	66.0
J. Fabricius	114.0	C. Shepard	20.5
R. Fisher	40.0	G. Shirn	3.0
A. Gagnon	1.0	P. Siegrist	17.0
H. Geller	153.9	D. Smyth	9.3
T. Jammallo	19.0	W. Tatem	1514.0
E. Jamros	566.0	H. Tourjee	162.5
W. Kearns	158.0	R. Trottier	160.0
R. Kemper	16.0	A. Vaskas	163.0
H. Labombard	32.0	L. Vivaldi	51.0
C. Lacasse	418.0	J. Willey	169.6
H. Lombard	13.5	A. Williamson	5.0
G. Maher	26.0	A. Zoito	647.5
		TOTAL	7808.0

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13. ABSTRACT

This report presents an approach toward attaining high life test reliability in subminiature ceramic barium titanate capacitors for transistor circuitry and demonstrates a procedure for selecting capacitors having guaranteed or assured lifetime (ALT) at various voltage and temperature stresses. The report presents the research supporting the plan of voltage selection testing which identifies those capacitors that have an assured useful lifetime (ALT). Other selection plans were surveyed but were rejected. The physics of material failure and reliability is discussed. Two lots of 1200 capacitors (0.01 μF and 0.033 μF) were voltage tested to identify capacitors which were predicted to fail life testing either prior to ALT or after ALT. Life testing was as long as 25,000 hours at several voltage and temperature conditions. The failure rate, after normalizing data, at 125°C, 25 VDC to ALT (30,300 hours) for the select 0.01 μF capacitors was 0.02% per 1000 hours. The failure rate after normalizing data at 125°C, 25 VDC to ALT (4775 hours) for the select 0.033 μF capacitors was 0.086% per 1000 hours. The failure rates to ALT for capacitors predicted to fail prior to ALT exceeded the failure rates of the select capacitors by factors approaching 100.

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